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A REVIEW AND EVALUATION
OF THE UTILIZATION OF SOLAR ENERGY

A THESIS

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A REVIEW AND EVALUATION

OF THE UTILIZATION OF SOLAR ENERGY

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SUMMARY

In our present industrial age, a tremendous amount of energy is consumed daily. At the present time, we depend largely on the solar energy stored in the fossil fuels -- gas, oil, and coal -- for our energy supplies. These fuels were formed many millions of years ago by a biochemical decomposition of vegetable and animal matter. However, these fuel reserves will not last forever. In fact, it will be shown that the maximum recoverable reserves will soon be depleted.

A large potential source of cheap energy is the sun. Nearly 1200 times as much energy as is presently being used falls daily on the United States. The purpose of this study was to review and evaluate the information available in the literature on the utilization of solar energy and to estimate the life of our fossil fuel reserves. Also the possibilities of providing adequate quantities of food for the growing world population by more intensive utilization of solar energy were examined.

The folowing areas were covered in this investigation:

(1) Solar Distillation,

(2) Conversion of Solar Radiation into Mechanical Energy,

(3) Solar Water Heating,

(4) Solar House Heating and Cooling,

(5) Solar Furnaces,

(6) Solar Cookers,

(7) Direct Conversion of Solar Energy into Electrical Energy,

(8) Photosynthetic Use of Solar Energy, and

(9) Use of Solar Energy in Space Travel.

Solar Distillation.--Solar distillation is one of the simple uses of solar energy and has been suggested for the purification of salt water brines. A number of stills have been designed and tested. They usually consist of a tray enclosed by a container with a transparent surface, perhaps glass, which admits radiation. The solar energy heats and evaporates the water. The water vapor condenses on the glass surface and is collected. Stills have been improved so that they can now produce fresh water at approximately \$0.82 per thousand gallons for a capital investment of \$4.50 per daily gallon. These costs compare very favorably with the cost of fresh water produced from salt water by other methods.

Conversion of Solar Radiation into Mechanical Energy.--The conversion of solar energy into useful work is entirely feasible. Solar heat engines employ the vapors produced in solar energy collectors as the working fluid. The temperatures of the vapors are made as high as possible by using multiple glass plate collectors or by using parabolic reflectors, so as to give higher engine efficiencies. The cost of these units, however, is so great that the solar engine is not economically attractive in the United States, where fuel is cheap and plentiful at the present time. Only in special cases, where power is not available or is available at a high cost only--such as in remote regions--can the immediate possibility of solar power be considered.

Solar Water Heating.--Solar water heating is already here. In 1951 approximately 50,000 units were in use in Miami alone, which indicates the wide-spread use of these units. Solar water heaters consist of a flat-plate solar energy collector and a storage tank in which the heated water is collected. Economic evaluations show pay-out times of 2.4 and 4.5 years, depending on the comparison with electrical or oil-fired water heaters. These figures indicate that the use of solar water heaters can be justified economically in suitable areas.

Solar House Heating.--Solar house heating, with its modest demands for temperatures, is another simple application of solar energy. Houses have been built that were heated entirely with radiation from the sun. However, it appears that emphasis will be placed on solar heating which can be supplemented with fuel heating on abnormally cold days or in continuing cloudy weather.

Economic studies indicate that solar house heating is slightly more expensive than heating with cheap natural gas. However, coal and oil heating costs can be reduced if the system is combined with a solar heater. If propane is used as fuel, large savings in heating costs are readily obtainable by use of the solar system. A rapid development of solar house heating is therefore expected, particularly in areas where the winters are not too severe.

Cooling with Solar Energy.--Cooling of houses with solar energy is possible but much more difficult than heating. The cost of the equipment is high and also the operating cost is about 3 times higher than for conventional systems. However, solar cooling systems may become competitive if they are combined with solar heating units.

Solar Furnaces.--The solar furnace has become quite important in the last decade. In this unit a parabolic mirror is employed to concentrate the solar radiation. Temperatures of approximately 5400 degrees F can be attained. These furnaces are being used for research work because they are highly flexible and because their operating temperatures are so high. Presently, 23 furnaces are in operation in the United States and 4 in other parts of the world. The costs of these furnaces are very great, but it is probable that many more will be constructed in the near future as the industrial requirements for high temperature materials become more pressing.

Solar Cookers.--Solar cookers have been designed and built since the end of the eighteenth century. Presently a cooker is mass produced by David-ayal Metal Industries Ltd. for distribution in under-developed countries. This cooker consists of a parabolic reflector that concentrates the solar radiation on a cooking vessel. A great many of these cookers could be sold if the price could be lowered below the current level.

Direct Conversion of Solar Energy into Electrical Energy.--The direct conversion of sunlight into electrical energy has been sought for several decades. Presently three devices are available for the conversion of solar into electrical energy: the thermocouple, the photogalvanic cell, and the photovoltaic cell. The efficiencies of the thermocouple and the photogalvanic cell are disappointingly low. The efficiency of the photovoltaic cell was recently raised to 11 per cent by scientists of the Bell Telephone Laboratories. However, although the efficiency is at least an order of magnitude greater than the best previous devices, the photovoltaic cell is still too expensive to compete with more conventional methods of power generation. Only under special conditions can this device be considered.

Photosynthetic Use of Solar Energy.--Photosynthesis is the most important reaction known to mankind, since it is the source of all food and fuel. Research is presently being conducted to increase the efficiency of this process. Among the research projects, those stand out that are based on the intensive cultivation of fresh water algae. Present costs of producing these algae are approximately $0.25 per pound. The price of competitive nutritive materials is $0.10 per pound. This puts algae out of consideration for the present at least. For the same reason, the production of fuel from algae, although technically feasible, is presently out of consideration. However, the first steps have been made in the direction of food production completely under human control.

Use of Solar Energy in Space Travel.--The vast amount of solar energy in space can be utilized to satisfy the needs of future space travelers. Oxygen and food can be produced in outer space by cultivation of fresh water algae. Electricity to power radio transmitters and receivers, and other electrical equipment can be provided by solar cells. Also, it seems entirely feasible that solar energy can be used to propel space ships over very large distances.

The life of our fossil fuel reserves was estimated to stress the importance of solar energy research. The estimate was based on the most plausible rate of increase in population and the per capita demand of energy. Also the limits of our food supplies were investigated for the same purpose.

Conclusions reached as a result of this study are as follows:

1. Some applications of solar energy are already economical under suitable circumstances. These applications include:

(a) Solar distillation,

(b) Solar water heating, and

(c) Solar house heating.

2. Research and development and the rising costs of fossil fuels will make other applications more attractive, and will increase the use of solar energy.

3. The fossil fuel reserves of the United States will be depleted by 2090 AD, if no new sources of energy are found and the fossil fuels continue to constitute the major source of energy. The fossil fuel reserves of the World as a whole will last to about 2060 AD.

4. It is apparent that the problem of providing enough energy for the growing population will become serious in the immediate future, and that solutions to this problem must be found.

5. The energy problem may be postponed by new developments in the future, but even so the problem will arise again.

6. Since the energy of the sun will last for a long time, it seems that the only ultimate solution to the energy problem is through the use of solar energy.

7. The amount of arable land will be insufficient to support the growing world population after about 1995 AD.

8. The production of food in the United States will be adequate until about 2040 AD. Then this country will have a food problem.

9. The ultimate solution to the food problem is the intensive cultivation of food sources such as algae that can be produced completely under human control.

CHAPTER I

INTRODUCTION

In our present industrial age, a tremendous amount of energy is consumed daily. In fact, we are so accustomed to an abundant supply of energy that we find it hard to conceive of a satisfactory way of life without abundant and economical power and heat.

At the present time, we depend largely on the energy stored in fossil fuels -- coal, oil, and gas -- for our energy supplies. However, these sources are distinctly limited. Although the world will not experience a shortage of fuel in our generation, the increasing population and the constantly rising demands for more energy will cause this problem to become acute in the near future.

In the last few years the atom has begun to supply a part of our energy requirements, and it seems likely that atomic energy will become more important in the future. However, the complicated safety devices and the waste disposal facilities that are required in the production of atomic energy make only the construction of large power reactors economical. For these reasons, atomic energy will probably be produced in multi-million dollar power stations in highly industrialized areas.

The possibility of using locally generated atomic energy in rural and non-industrialized areas seems remote due to the high costs of the atomic reactors. It seems likely that the sun's energy can be used advantageously in those places. Unlike atomic energy, solar energy has no critical mass, presents no health hazards, and does not require expensive waste disposal facilities. Another definite advantage is the smaller size of the units in which the solar energy is utilized.

The sun showers far more energy on the earth's surface than is needed at the present time. It is reported (1) that the earth intercepts 1×10^{18} horsepower-hours of energy per annum while the present world-wide energy consumption is estimated at 4.9×10^{13} horsepower-hours. This means that the energy supply is approximately 20,000 times greater than the present world-wide demand. Even in the highly industrialized United States the sun supplies 1,200 times as much energy as is now being used.

Although solar energy is immense in quantity, it is relatively low in intensity, and a considerable area is needed to collect large quantities of energy. This low intensity and the intermittency of the solar radiation caused by clouds and night are drawbacks to the extensive use of solar energy.

The basic problem in the economic use of solar energy is that of reducing the size of the equipment and of minimizing the capital expenditure. Any solution to this problem will depend to a large extent upon the full recognition and the adequate treatment of the conversion of solar energy.

A considerable body of literature on the utilization of solar energy is available. The purpose of this study was to review and evaluate critically the information with the object of pointing out areas and research efforts that appear to be the most promising and, perhaps, the most necessary if the impending crisis in the supply of food and power for the dangerously increasing population of the world is to be minimized or averted.

CHAPTER II

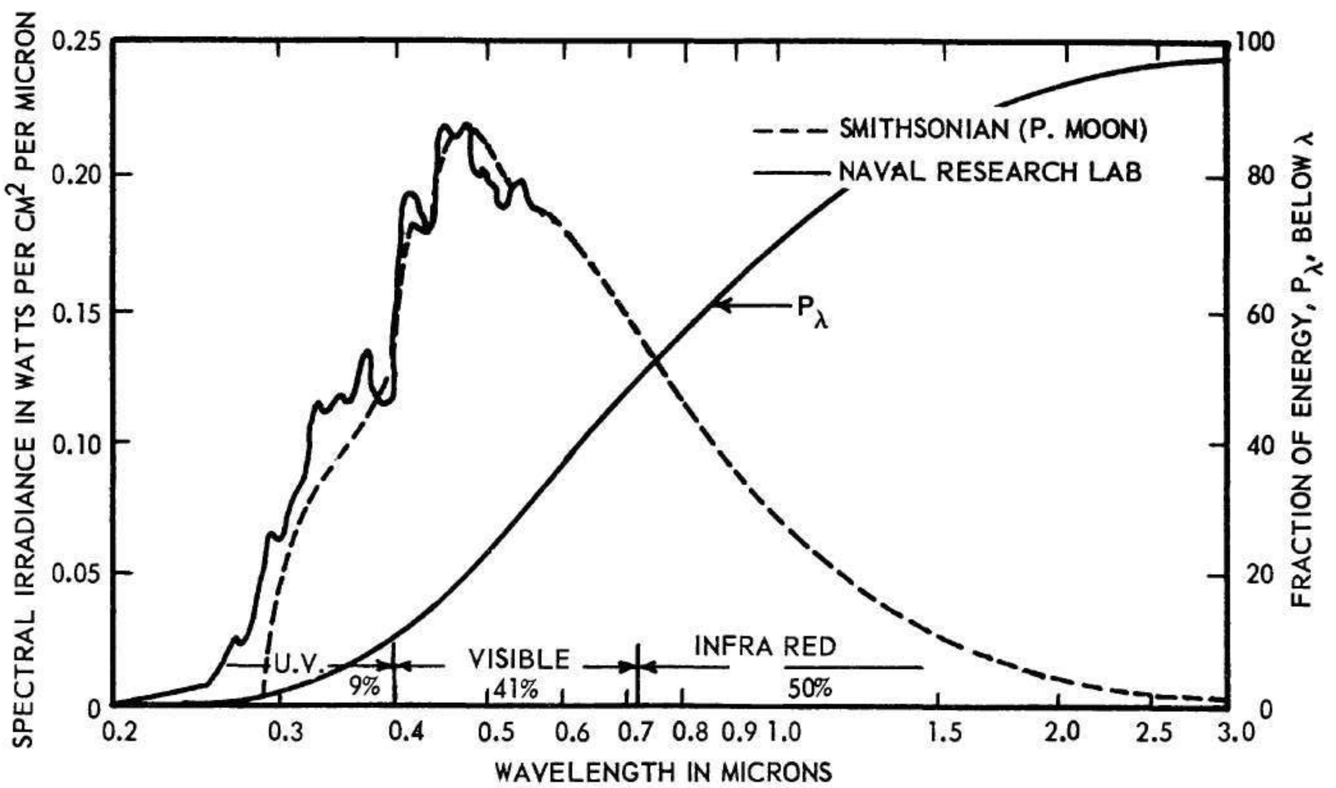
NATURE AND AVAILABILITY OF SOLAR ENERGY

Every second of every day, the sun fuses approximately 564 million tons of hydrogen into 560 million tons of helium. In this process, four million tons of matter are converted into energy which is radiated into space. For most practical purposes this energy can be thought of as light and heat.

The amount of solar energy that reaches the earth's atmosphere is known within a few per cent. The most recent value is given by Johnson (2) as 2.00 ± 0.04 calories per minute per sq. cm.

The spectral distribution of the solar energy just outside the earth's atmosphere is presented in Figure 1. Of the total incident energy 9 per cent lies in the ultraviolet region, 41 per cent in the visible, and 50 per cent in the infrared. For all practical purposes the energy lies between the wavelengths of 0.22 and 3.0 microns.

About 35 per cent of the energy intercepted by the earth's atmosphere is immediately reflected into space. The remaining energy travels on down through the atmosphere where depletion of the direct beam takes place by scattering and absorption (3), so that only about 46 per cent of the extraterrestrial energy reaches the earth's surface. Scattering is caused primarily by air molecules, dust, and to a certain extent by water vapor. The principle absorbing agents in the atmosphere are water vapor, ozone, carbon dioxide, and dust particles.

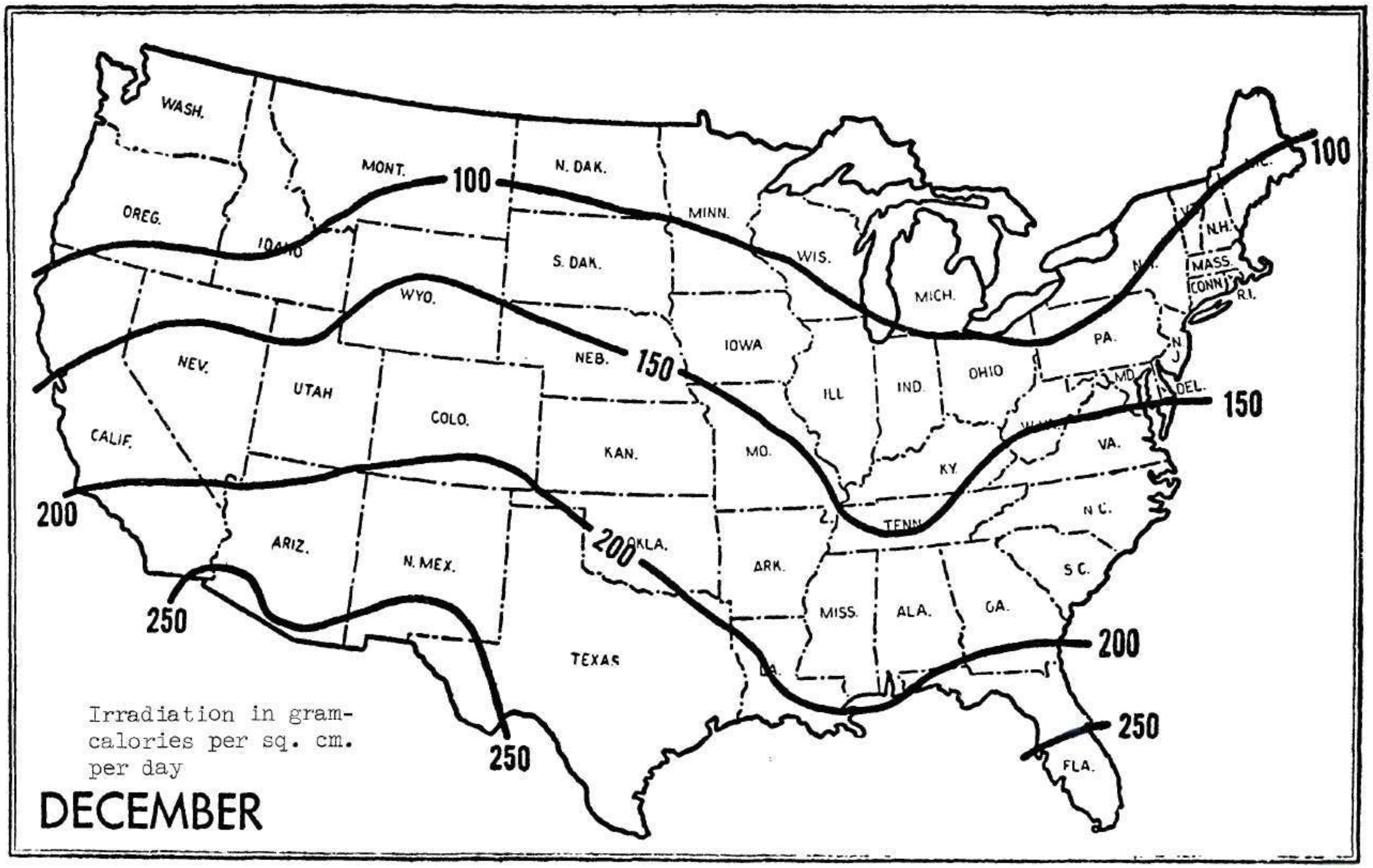


Reproduced from Fritz, S., "Transmission of Solar Energy through the Earth's Clear and Cloudy Atmosphere," in *Transactions of the Conference on the Use of Solar Energy – the Scientific Basis*, University of Arizona Press, Tucson (1958).

Figure 1. Spectral Distribution of the Solar Energy Outside the Earth's Atmosphere.

Because solar energy must be utilized at the surface of the earth, the design engineer needs to know accurately the availability of the supply. For cloudless skies fairly good estimates can be made of the amount of solar energy reaching the ground (4). But for overcast skies, we would have to know not only the thickness of the cloud, but also the mean free path of the light through the cloud which depends on the drop size distribution and the liquid water content of the clouds. Fritz (4) mentions that it is easier to measure the solar radiation in order to estimate the cloud thickness and the mean free path than the other way around.

Faced with this impasse, we have two choices. One way to obtain the value of the incident energy is to measure it wherever and whenever it is wanted. This, of course, is a very reliable but also very expensive approach. The other alternative is to use charts showing the average amounts of solar energy received at the earth's surface. One of these charts, prepared by Fritz and MacDonald of the U. S. Weather Bureau, is presented in Figure 2. The probable error in the data is of the order of five per cent or less (5). If the charts are used at points other than those at which the radiation was computed or measured, there is an additional source of error which can be ascribed to atmospheric pollution, elevation, ground reflection, or degree of cloudiness. Therefore caution must be used in applying the values in large cities, mountainous areas, and on the shores of large bodies of water.



Reproduced from Fritz, S., and T. H. MacDonald, *Heating and Ventilating, 49,* 147 (August, 1952).

Figure 2. Sample Chart of the Average Amount of Solar Energy Received in the United States.

CHAPTER III

DISTILLATION WITH SOLAR ENERGY

It is known that the availability of fresh water is rapidly becoming a major concern to America and the World. Even in many non-arid countries, the natural water supplies do not satisfy the current demands. In the United States the water problem is not yet acute, but it has been stated that it may be our primary domestic problem in fifteen or twenty years (6). New sources of fresh water for domestic use and for agricultural purposes are desperately needed.

In many regions with low fresh water supplies, water is available, but at a salinity level which makes it unfit for drinking and irrigation. Several processes may be employed, however, to produce fresh water from this salty or brackish water. Calculations and experiments conducted by the Heliolaboratory of the USSR Academy of Sciences indicate that the distillation process is the most practical of the existing water demineralization methods (7).

The amount of energy required to produce a pound of fresh water from sea water by distillation is approximately 1,080 BTU, an appreciable amount of energy. In many locations in the world the cost of the fuel to operate a conventional still would be prohibitive. In these places, distillation with solar energy could possibly be utilized to produce usable water.

During the past century, numerous solar stills have been designed and constructed. These stills can be classified into two groups:

(1) High temperature stills, and

(2) Low temperature stills.

The high temperature still utilizes a concentrator that focuses the solar radiation on a boiler to produce steam. This steam may then be used in conventional distillation equipment or it may be condensed to give fresh water.

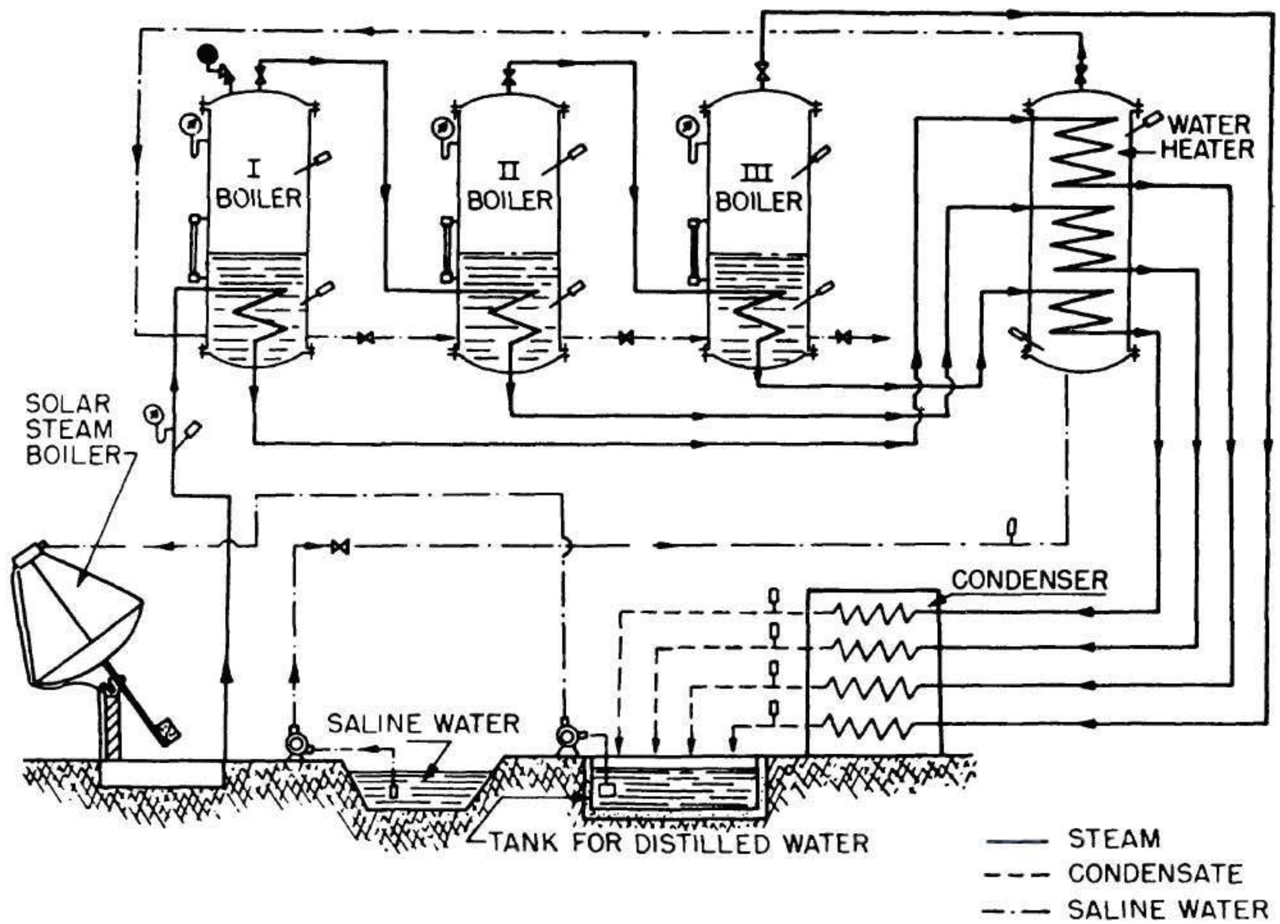
A diagram of this still, presented in Figure 3, shows how the steam generated in a solar collector operates a conventional multiple effect evaporator.

High temperature stills have not been very popular. This is mainly due to the difficulties and the problems connected with the concentration of solar energy. These problems were listed by Telkes (8) as

(a) Only the direct part of the solar beam can be focused. The diffuse radiation which is seldom less than ten per cent is lost.

(b) To heat the still a concentrating device is required to focus the solar radiation on a boiler. This can be accomplished only if the concentrator is continuously moved with sufficient precision. This is a rather difficult problem that requires complex machinery for satisfactory operation, and

(c) Single-effect stills operating with solar energy are not economical. Multi-effect stills require complex equipment and auxiliary power sources to maintain the vacuum.



Reproduced from Baum, V. A., "Prospects for the Application of Solar Energy, and some Research Results in the U.S.S.R.," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955)*, Stanford Research Institute, Menlo Park (1956).

Figure 3. Diagram of a High Temperature Solar Still.

Eibling, Thomas and Landry (9) investigated the economics of fresh water production in high temperature stills. Their study indicates that the lowest production cost is $3.25 per 1000 gallons, including amortization. They stated that with additional research the cost may decrease to about $2.20 per 1,000 gallons.

For additional information a comprehensive bibliography by Löf (10) may be consulted.

The low temperature still consists essentially of a shallow tray enclosed by a transparent container that serves to admit the solar radiation. The solar radiation heats the water in the tray to a temperature of 150 to 160 degrees F. The water evaporates from the tray and condenses on the transparent surface where the heat of condensation is dissipated to the ambient air.

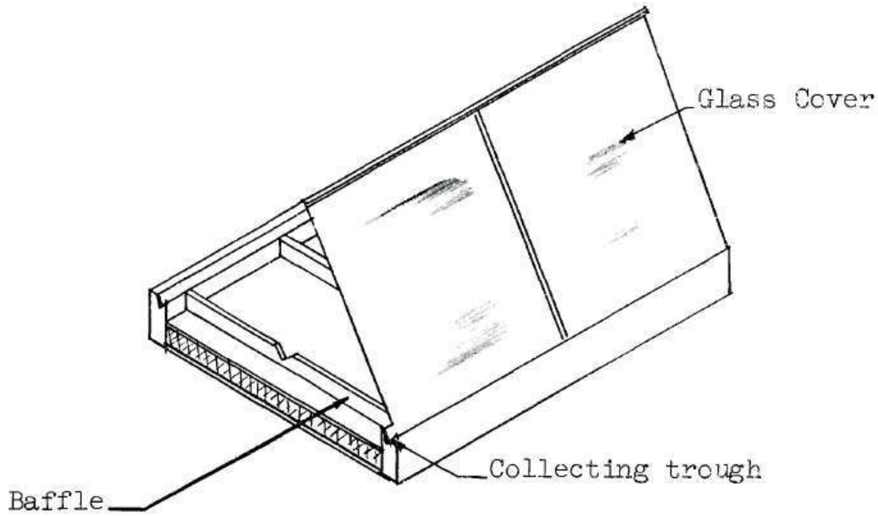
Three of the most important designs will be discussed very briefly to show the present status of the low temperature solar stills. These designs are:

(a) The roof-type still,

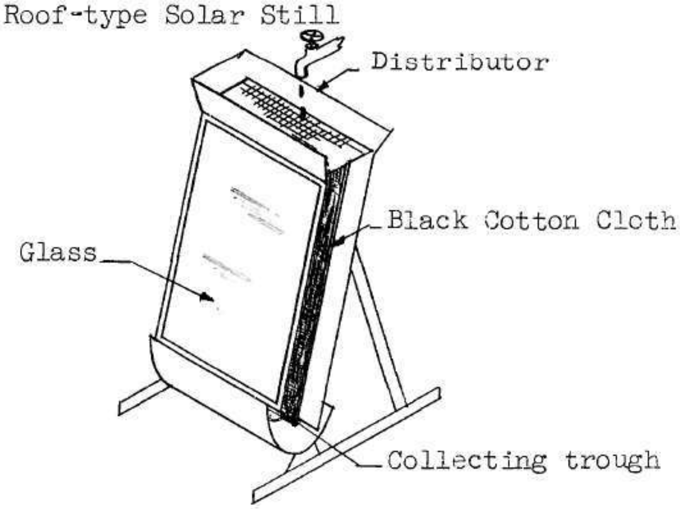
(b) The flat-tilted still, and

(c) The tubular still.

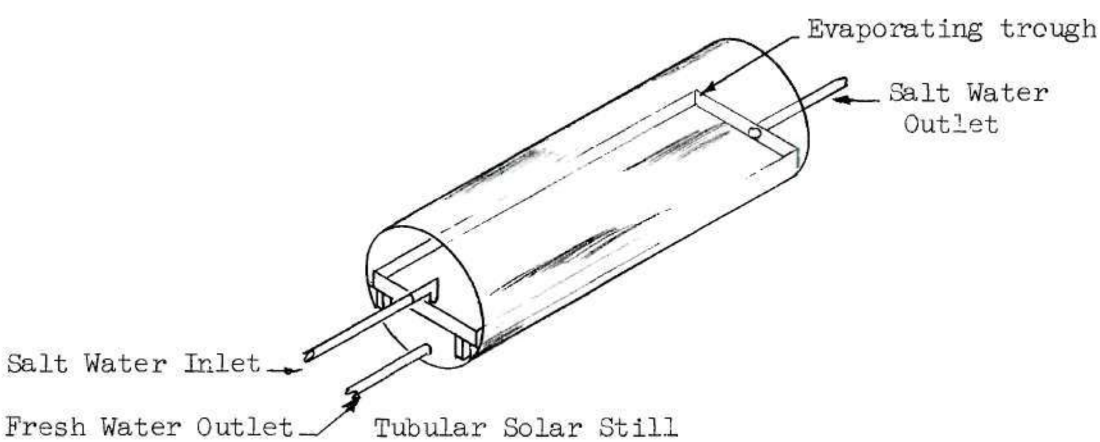
The roof-type still, shown in Figure 4, consists of a black tray hermetically sealed by a roof constructed of either glass or plastic. The bottom of the tray should be insulated to increase the efficiency of the still by reducing heat losses. The solar rays penetrate the transparent roof and heat the water contained in the tray. The evaporated water condenses on the glass roof and flows down into collecting channels at the lower edges of the glass panes. From here it discharges through a tube.



Roof-type Solar Still



Flat-tilted Solar Still



Tubular Solar Still

Figure 4. Low Temperature Solar Stills.

The first large roof-type still was constructed in 1872 to provide drinking water for the miners of Las Salinas in Chile (12). This still covered 51,000 sq. ft., and its largest yield was reported as 6,000 gallons daily. The still consisted of wooden evaporator trays, waterproofed by asphalt. Glass panes, in the form of an inverted V, covered the trays. The total price of the installation, including all accessories such as pumps, storage facilities, etc., was $250,000 (12).

A similar still was designed by Telkes, and one with a base area of 200 sq. ft. was built at Cohasset, Massachusetts in 1951. Its maximum daily capacity was reported as 0.14 gallons of water per sq. ft. of base area (13).

Another still of this type was constructed by Nebbia in Bari, Italy. This still with a glass area of 108 sq. ft. yielded 4.9 gallons of fresh water per day (14).

A modification of the roof-type solar still was prepared by Löf in 1957 (15). His design differs from the ordinary roof-type still in that it utilizes a deeper tray that can hold a considerable amount of water. A small prototype of his design was built at a test station near Port Orange, Florida and is presently being tested.

The roof-type still operates very efficiently if a sufficient amount of insulation is used to prevent heat losses from the evaporating tray. Efficiencies from 50 to 65 per cent are reported (16).

The roof-type stills described above receive the radiation on a sloping surface. However, to receive the maximum amount of radiation, the heat absorbing surface should be tilted depending on the latitude at which the still operates. This consideration resulted in a new design by Telkes. This type of still, called the flat-tilted still, is shown also in Figure 4.

The flat-tilted still consists of a black evaporator pad supported freely between two panes, the front one being transparent to admit the solar energy. Sea water is fed to the top of the evaporator pad through a distributor. The water seeps down through the pad and evaporates. The evaporated water condenses on the glass pane and is collected in a trough. The concentrated brine collects in channel at the lower edge of the porous pad and is discharged.

Water yields of the roof-type and flat-tilted stills of equal evaporator areas have been compared (17). Flat-tilted stills yielded 26 to 48 per cent more water than the roof-type stills, primarily because they intercepted more solar energy per square foot of evaporating area.

A third type of still that has received considerable attention is the tubular still. The tubular still, portrayed finally in Figure 4, consists of a horizontal glass tube fitted with end plates that support a shallow tray. Salt water is pumped into the tray from which it evaporates. The water condenses on the inside of the glass tube and collects in the bottom. The water is discharged through an opening in the end plate. This design does not require insulation since the heat loss from the bottom of the tray is reduced by the shielding effect of the glass tube.

During World War II a still of this type was designed by Telkes to be used by flyers forced down at sea. An inflatable still made of vinylite was constructed to float next to the life raft. The transparent plastic supported a black porous pad from which the water evaporated.

Presently, this type of still is used as standard equipment on life rafts (18).

A tubular still with a tray 4 feet wide by 51 feet long, covered with thin sheet plastic, was built and studied by Howe (19). He reported a maximum yield of approximately 0.10 gallon per day per sq. ft. of collector surface. Costs of materials for large plastic stills were listed as $7.50 per daily gallon of fresh water, whereas glass covered stills cost $13.00.

The economics of the low temperature still has been investigated by Löf (10). Roof-type stills appear to be economical, according to his estimates, producing water at $1.65 per thousand gallons. With improvement in design and operation this cost can be reduced to $1.00 per thousand gallons. The initial investment for the roof-type still is estimated at $4 per daily gallon of fresh water (20).

The cost to produce fresh water in the flat-tilted still was estimated by Telkes (21) following the procedure used by Löf (10), as reported by the Office of Saline Water. The operating cost was given as $0.82 per thousand gallons at an initial investment of $4.50 per daily gallon of fresh water. Using plastic in place of glass, the operating cost may be reduced to $0.68 and the initial investment to $2.75.

The costs of producing fresh water in solar stills and in conventional equipment, and the necessary capital investments are summarized in Table 1.

From inspection of the costs reported in Table 1 it can be concluded that fresh water made in solar stills is more expensive than water produced in conventional purification equipment. However, it can

Table 1. Summary of Costs to Produce Fresh Water in Solar Stills and in Conventional Equipment

Water Purification Equipment	Operating Cost* Dollars per Thousand Gallons	Capital Investment Dollars per Daily Gallon
High Temperature Still	2.20 - 3.25	-
Roof-Type Solar Still	1.00 - 1.65	4.00
Flat-Tilted Solar Still	0.68 - 0.82	2.75 - 4.50
Tubular Still	-	7.50 - 13.00
Conventional Water Purification Equipment (22)	0.16 - 0.50	3.00 - 4.00
Multiple-Effect Fuel Operated Stills (22)	3.80	6.30

*Cost including amortization and maintenance.

be seen that the cost is considerably lower than the cost of water produced in multiple-effect, fuelled stills.

Eventually, after adequate research and development, the cost of water from solar stills may become comparable to the cost obtained with conventional equipment. It may even become cheap enough so that it can be used for irrigation purposes. This, however, would require an operating cost of less than 12 cents per thousand gallons, which is presently the maximum that can be afforded for irrigation in California (23).

CHAPTER IV

CONVERSION OF SOLAR RADIATION INTO MECHANICAL ENERGY

Most of the energy used today is obtained by burning fossil fuels. This energy originated in the sun and has been stored for many thousands of years in these fuels. Solar energy, however, may be converted directly into mechanical work by heat engines which use low pressure steam or other vapors as the working fluid, and by hot air engines.

The work of Auguste Mouchot in France represents one of the earliest attempts to convert solar radiation into useful work. He designed and built several experimental solar-power systems around 1870. Conical shaped mirrors of 54 to 215 sq. ft. area were used to generate steam at pressures up to several atmospheres to operate engines and water pumps. The efficiency of these systems was quite low; only 3 per cent of the solar heat collected by the mirrors was converted into useful work (24).

In the United States, John Ericsson experimented with similar systems. His design involved both steam and hot air engines.

In 1901, the famous Pasadena solar engine was erected on an ostrich farm. The reflector was a truncated cone with a maximum diameter of 33 1/2 feet and a minimum diameter of 15 feet (25). This reflector concentrated the solar radiation on a boiler. The steam generated was utilized to operate a 4 1/4 horsepower heat engine. This engine was connected by a belt to a centrifugal pump that could deliver 1400 gallons of water per minute.

Around 1900, Willsie and Boyle developed a system in which two liquids were used. Solar radiation was absorbed in water which was then used to evaporate ammonia, ether, or sulphur dioxide. The vapor operated an engine that developed 15 horse-power (26).

Also around 1900 a solar engine using a binary cycle was built by Krenn; the engine could operate continuously (27). Three parabolic mirrors concentrated the solar radiation on an evaporator containing mercury. The mercury was vaporized and the vapors were expanded in a turbine which operated an engine. A condenser, attached to the turbine, liquefied the mercury vapor at approximately 220 degrees C. The latent heat of the mercury was utilized to produce steam in a second cycle. The steam generated was used to operate a second engine. On cloudy days and during the night the apparatus continued operation without interruption because the relatively large amount of mercury in the mercury boiler acted as a heat storage reservoir.

In 1913 one of the most important of historical solar-power attempts was undertaken by Shuman and Boyd, sponsored by the Eastern Sun Power Company Limited (28). Parabolic reflector troughs, totalling over 13,000 sq. ft., were constructed at Meadi in Egypt for use in an irrigation project. The absorbers generated steam which operated a 100 horse-power engine. Enough water was pumped to irrigate over a thousand acres of land. This system was abandoned during World War I since it was not economically competitive with other irrigation systems.

The solar engines described above are shown schematically in Figure 5. The solar energy is absorbed by the working material, such as steam or air, in the collector. The heat is then transferred to the engine where it is converted into mechanical energy. The heat not utilized is rejected in a condenser, a cooler, or a radiator.

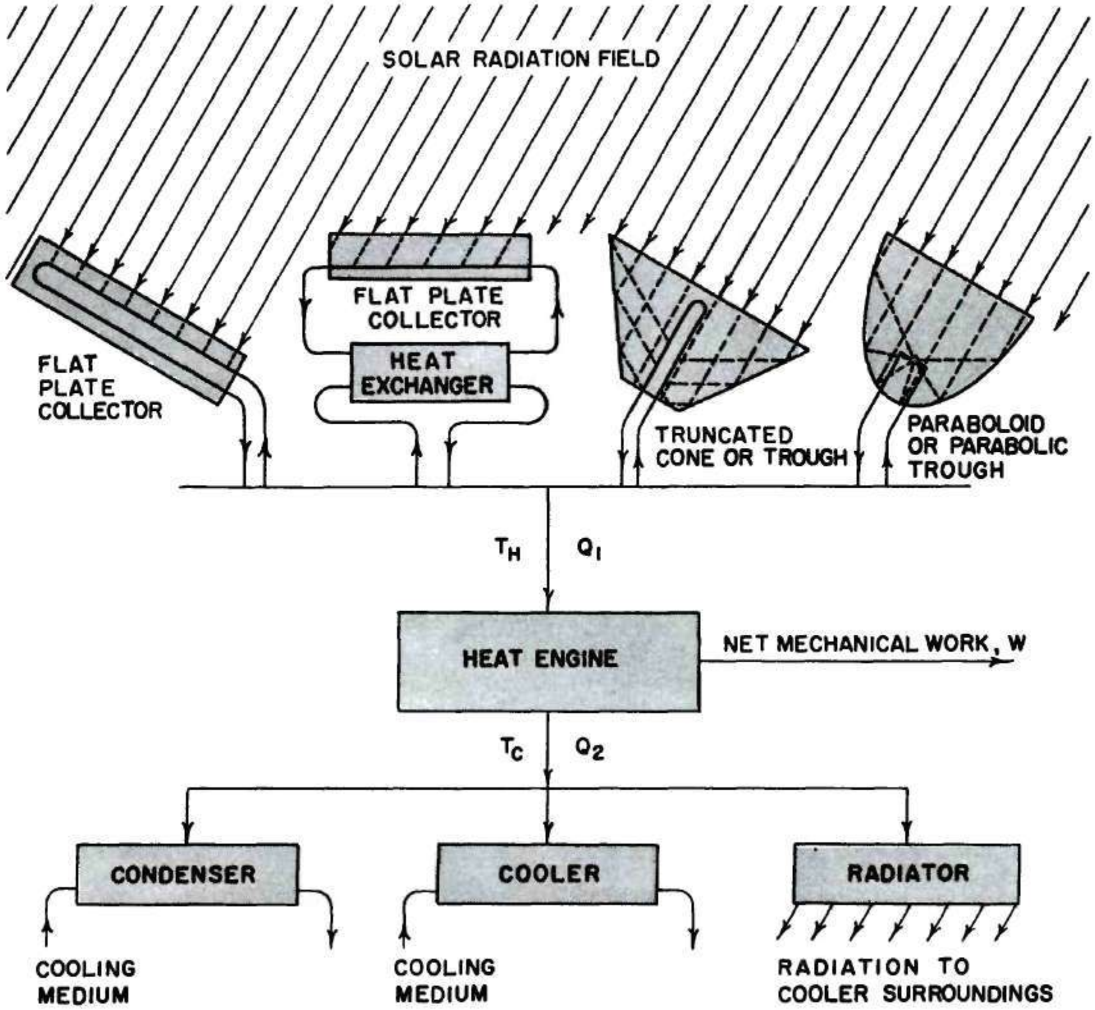


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Figure 5. Components of a Solar Engine.

The maximum efficiency of the engines is fixed by the Second Law of Thermodynamics which states that no heat engine operating between fixed temperature levels can exceed the Carnot efficiency. This law can be expressed mathematically by the following equation:

$$\text{Efficiency}_{\text{max.}} = \frac{T_H - T_C}{T_H}$$

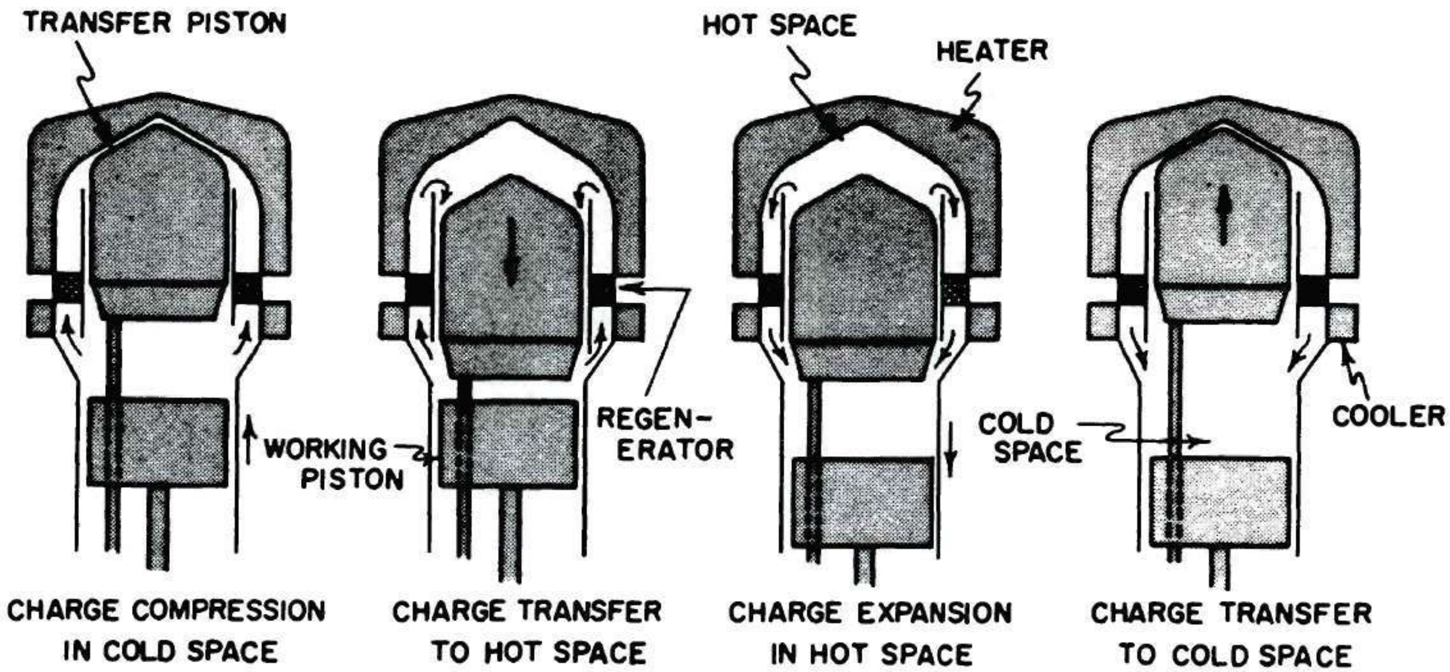
where T_H = temperature of the heat source, °R

T_C = temperature of the heat sink, °R.

This law places a limitation on the maximum conversion of heat into work. To increase the efficiency, the difference between the extreme temperatures must be enlarged. This is the reason behind the use of collectors with optical concentration. For medium temperatures, cylindrical mirrors with nearly parabolic cross-sections are used. For very high temperatures paraboloidal mirrors are employed. Flat-plate absorbers are satisfactory only for low temperature collection.

A heat engine which has been in the spotlight in recent years is the hot-air engine. A simplified version is shown in Figure 6.

The operation of this engine is as follows. The gas is first compressed in the cold space of the engine. Then, by means of a transfer piston it is transferred into the hot space surrounded by the engine heater. Here the air charge is heated and the gases, now at increased pressure, are again transferred to the cold space where the high-pressure gas expands to activate the working piston. Data on an air engine rated at 0.25 horse-power at 2500 RPM. show a low overall thermal efficiency of 4 per cent when operating at heater and cooler temperatures of



Reproduced from Jordan, R. C., and W. E. Ibele, "Mechanical Energy from Solar Energy," in ***Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955),*** **Stanford Research Institute, Menlo Park (1956)**

Figure 6. Schematic Diagram Showing the Operation of a Hot Air Engine.

approximately 1050 and 250 degrees F, respectively (29).

No rigorous economic evaluation of solar heat engine systems has been found. However, it is probable that the cost of the engine itself would be comparable to the cost of conventional engines if it could be mass produced. But the additional heat collecting equipment, required in a solar heat engine system, would add considerably to the cost. Annual fixed charges on this additional expense are estimated to make the operating costs of solar heat engines two to three times as high as the cost of fuel used in conventional engines (30).

The conclusion to be drawn is that the conversion of solar energy into useful work is entirely feasible. However, the cost of the necessary heat collecting apparatus is so great in proportion to the power developed, and consequently so also are the annual fixed charges, that the production of work from solar heat is not economically attractive in the United States, at least at the present time. Unless the cost of oil and coal becomes much higher than the present value, it seems unlikely that solar-plants will become economical in the near future. When power is not readily available or is available only at a high cost, such as in remote regions, the immediate possibility of solar power can be considered.

CHAPTER V

SOLAR WATER HEATERS

During the last two decades, solar water heaters have become increasingly popular, especially in Florida, California, and Arizona. In 1951 approximately 50,000 solar water heaters were in use in Miami alone; this indicates the widespread use of these units (31).

The solar water heater is installed for two reasons:

(1) To provide hot water where other heat sources are unavailable, and

(2) To provide hot water where the initial cost and the operating expense of a solar water heater are less than the cost of owning and operating other types of water heating systems.

A solar water heating unit, shown in Figure 7, consists of an absorber to convert the radiant energy from the sun into heat and to transfer this heat to water flowing through the unit and a storage tank in which the heated water is collected. The absorber frequently forms part of the roof; the storage tank is usually located higher, in the attic or in the chimney. This arrangement makes a pump unnecessary since the change in the density of the water with temperature causes and maintains the flow.

The heart of the heating system is the absorber. It consists of a length of copper tubing welded to a sheet of blackened metal. It is

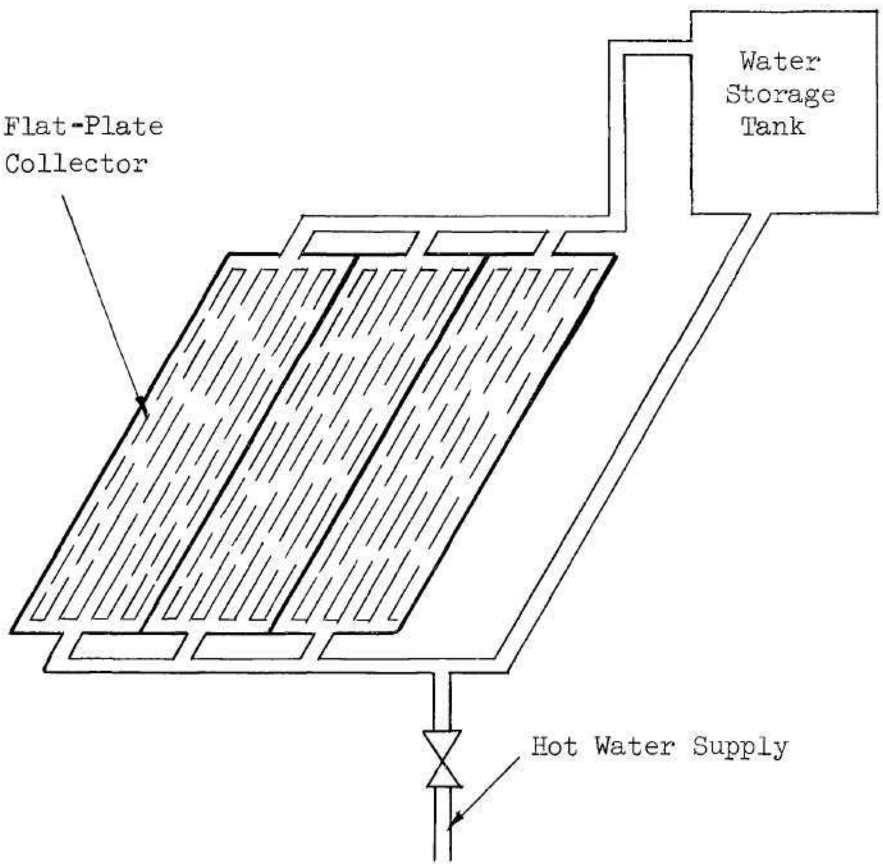


Figure 7. Solar Water Heating Unit.

usually covered with one or more layers of glass to reduce heat losses. The bottom of the absorber is also heavily insulated for the same reason.

To be most efficient, the absorber should intercept the solar radiation at a 90 degree angle. This would require a daily rotation of the unit about a North-South axis. Such absorbers have been built, but they are quite expensive. For this reason, the absorbers are usually installed in a fixed position.

For the best year-round performance, the angle of inclination of the absorber to the horizontal should be equal to the latitude (32), and it should face due South in the Northern hemisphere. To increase the output in the winter, it is advantageous to increase the angle of tilt to a maximum of 15 degrees more than the latitude (32).

The size of the absorber to heat a quantity of water can be calculated from the average production which has been reported as 1.7 gallons of hot water per day per sq. ft. of collector surface (33). The absorber can be built out of blackened copper sheet, 0.02 inch thick, or blackened aluminum sheet, 0.04 inch in thickness (34). Approximately 4 to 5 feet of 3/4 inch pipe are used per square foot of glass area (35).

For additional information on this type of collector, the reader is referred to a discussion by Robinson (36), and papers by Hottel (37), (38).

Since the solar energy can be collected only during a limited period of the day, provisions must be made to store hot water for use during the night and early morning hours.

The tank size can be based on the storage of 15 to 20 gallons for each person who uses the system. It is customary to equip the storage tank with an electric booster, so that electricity can be used to heat the water on days when the sun does not shine.

An economic evaluation of solar water heating systems was prepared by the author. The evaluation was based on a monthly collection of 20,000 to 25,000 BTU per square foot of collector area, which may be expected in the sunny parts of Florida. Using the larger figure, the yearly value of the energy collected per square foot of collector area is $0.60 on the basis of oil at $0.14 per gallon, burned with an efficiency of 50 per cent, or $1.17 on the basis of electricity at 4 cents per kwhr. (39).

The installed cost of solar water heaters in 1950 in Florida was $4.50 per square foot of collector area including a storage tank for the heated water (39). The price of an electric water heater is approximately $95 for a 30 gallon unit, while an oil-fired unit of the same capacity would cost around $100. These 30 gallon heaters are capable of heating approximately 50 gallons of water per hour to 150 degrees F. If it is assumed that an average of 80 gallons of hot water is consumed daily per family, a solar heater with an area of 56 square feet could be used to supply the heated water. The cost of this unit would be approximately $250. The annual saving in fuel would be $65 or $34 depending on the energy source with which the solar heater is compared. These figures show that the pay-out time of the solar water heater is 2.4 years if compared with an electric water heater, and 4.5 years if compared with an oil fired unit.

This economic evaluation indicates that the use of solar energy for water heating can be justified on economic grounds in suitable areas like Florida, California, and Arizona. In other locations, with much less sunshine, solar heaters might be attractive, but an economic study should be made first to be sure.

CHAPTER VI

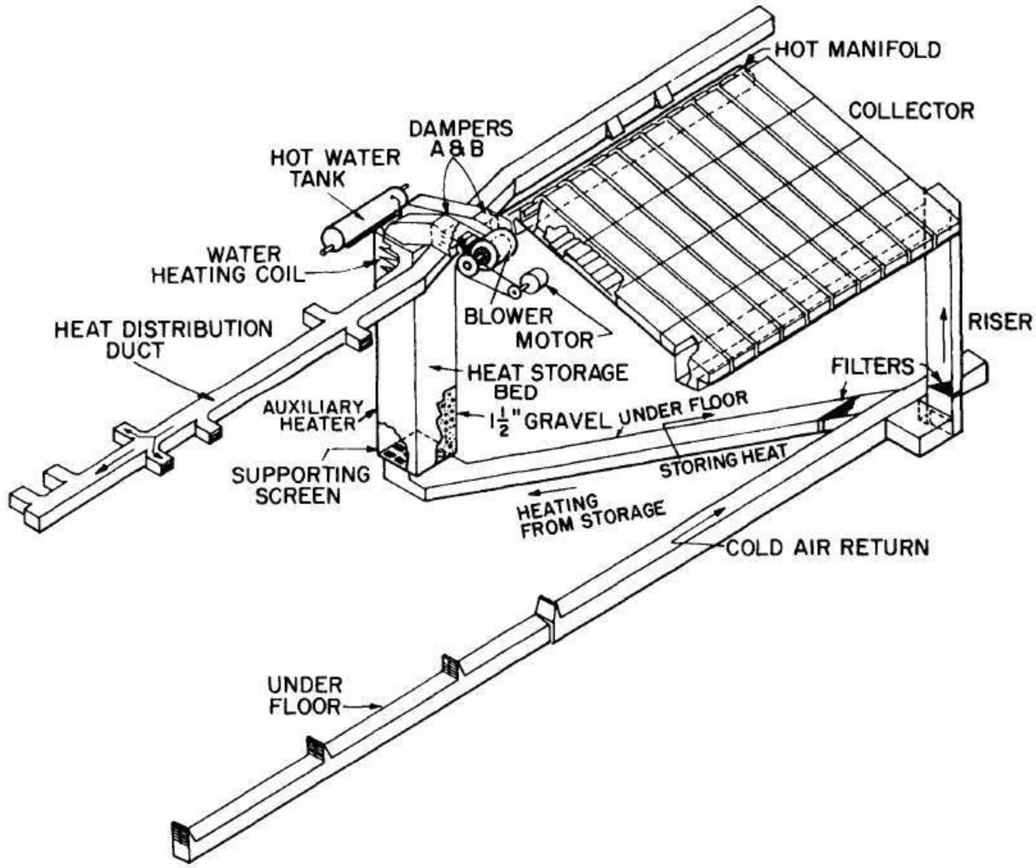
SOLAR HOUSE HEATING AND COOLING

The first attempts to use solar energy for house heating purposes were made around 1930 in the United States.

At first, large south-facing windows were used as an aid to domestic heating. Two glass panes with an air space in between were generally employed. These windows, provided with shutters, admitted large amounts of radiant energy on clear days and some energy even on partly cloudy days that resulted in a saving of fuel. Thirring (40) states that in latitudes between 40 and 43 degrees, fuel bills can be reduced by 30 per cent and in some cases even by 50 per cent with these windows. However, this heating system is not too satisfactory. During bright winter days it is hard to keep the house from overheating while at night heating becomes impossible. Another disadvantage of this heating system is due to the fact that the windows also admit heat during the summer when heat is least desired.

Solar heating systems that employ a flat-plate collector are much more practical, especially if some method of heat storage is provided. A heating system consisting of a solar energy collector, a heat storage reservoir, and a heat distribution system is shown in Figure 8.

The operation of this heating system is as follows: During daytime, cold air is supplied from the rooms or from the bottom of the storage bed to the collector where it is heated. The heated air is then blown



Reproduced from Löf, G.O.G., "Solar House Heating," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955)*, Stanford Research Institute, Menlo Park (1956).

Figure 8. Solar House Heating System.

to the rooms or the top of the storage bin. At night, house heating from storage is accomplished by the automatic shifting of two dampers so that air returning from the rooms passes upwards through the storage bed where it is heated prior to distribution to the house rooms by a blower. An auxiliary gas-fired heater is mounted in the air duct so that it will raise the temperature of the air to the desired level, if necessary. Thermostats and damper motors are provided for complete automatic operation of the system.

The first solar heated house of this type was built in 1939 at M.I.T. Since that time, several others have been constructed by Telkes (41), (42), Löf (43), and Bliss (44).

The design of solar heated houses employing flat-plate collectors was treated by Whillier (45).

The two major problems in solar house heating are the collection and the storage of heat. The collection of the heat is accomplished in a flat-plate collector covered with one or more layers of glass. This collector is usually oriented in a fixed south-facing position. The heat is stored in a material with a sufficiently large heat capacity, usually water or gravel. The disadvantage of these materials is in the large quantity that is required.

Dr. Telkes (46) devised a heat storage system that has operated successfully in experimental houses for several years. In this system, the heat is stored in Glauber salt ($Na_2SO_4 \cdot 10\ H_2O$). This salt absorbs heat as it liquefies at 90 degrees F. The material can store 9,500 BTU per cu. ft. A cost comparison made by Telkes indicates that this heat of fusion type of storage is less expensive than others.

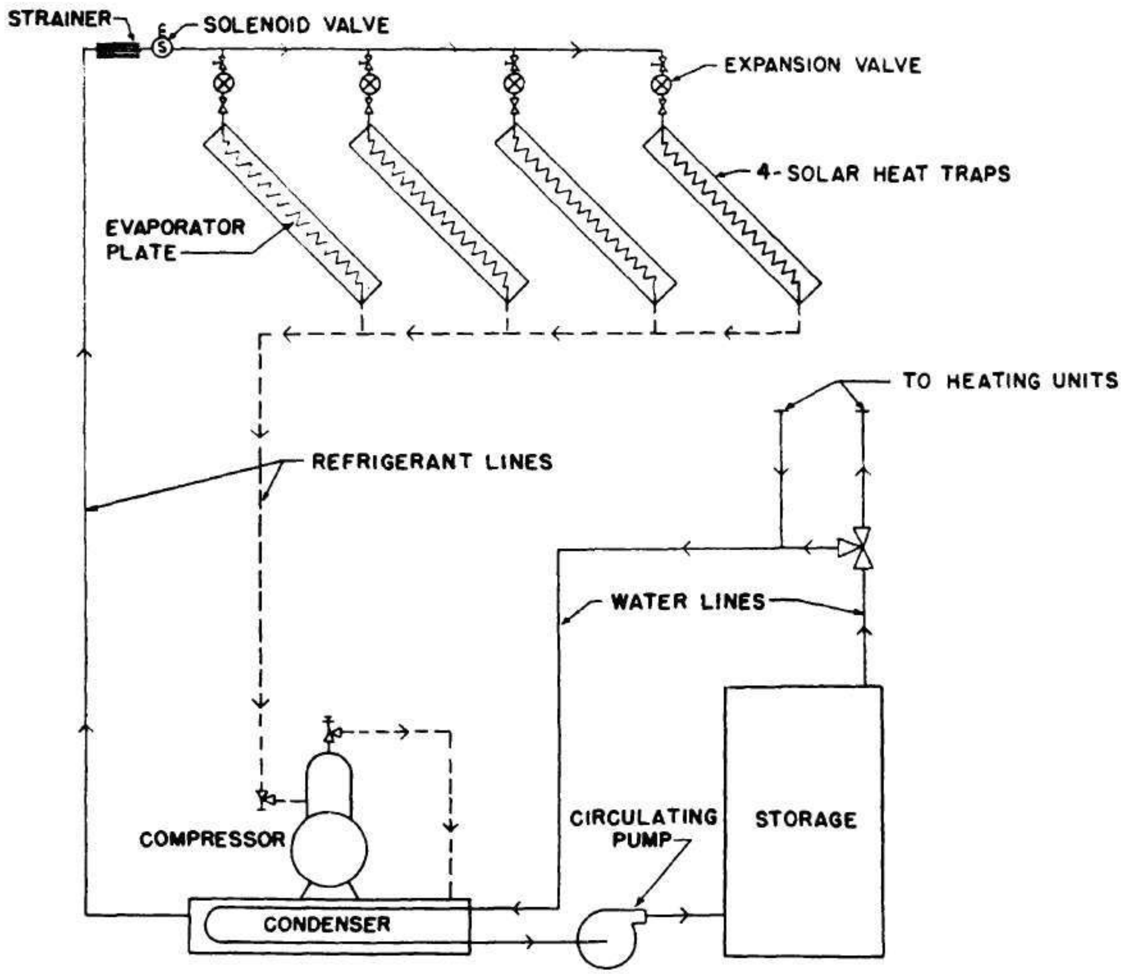
A new type of solar heating system was developed by Sporn and Ambrose in 1949 (47). This device utilizes a heat pump and is shown in Figure 9. It consists of a solar evaporator, a condenser, a compressor, and a heat storage reservoir.

The compressor circulates the refrigerant between the evaporator, which is kept at 60 degrees F or lower, and the condenser, which is usually about 110 degrees F or higher. The refrigerant changes from a liquid to a gas in the evaporator where the necessary heat is obtained from solar radiation. The refrigerant completes the cycle when it condenses to a liquid in the condenser and gives up the latent heat to the circulating water. The heated water is then delivered to the storage tank for use in the heating system.

The heat pump is essentially a device to raise the temperature level of a large amount of energy by the expenditure of a smaller amount of work energy (electrical or mechanical). At present, the coefficient of performance of the heat pump is 4, or in other words 4 units of energy are made available for space heating upon the expenditure of 1 energy unit in the form of work. No fossil fuel would be needed if the power requirements of the compressor could be supplied by solar energy.

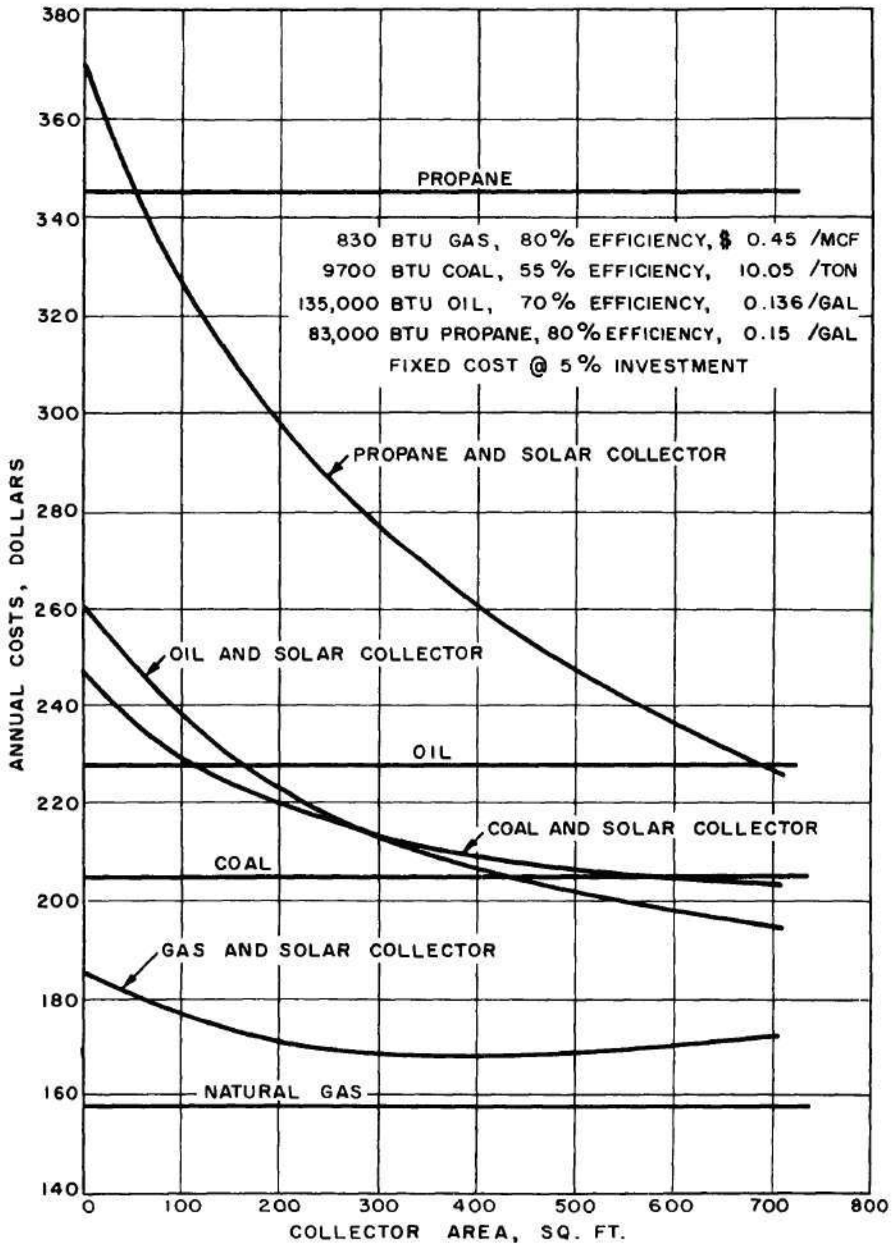
A more extensive discussion of the heat pump is available in the bibliography published by the Edison Electric Institute (48).

Economic evaluations of the solar heated house were made by Whillier (45), Löf(43), and Bliss (44). Whillier compared the cost of solar heating to the cost of heating with conventional fuels, based on solar radiation data taken at Blue Hill, Mass. His results are presented in Figure 10.



Reproduced from Sporn, P., and E. R. Ambrose, "The Heat Pump and Solar Energy," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955),* Stanford Research Institute, Menlo Park (1956).

Figure 9. Solar Heat Pump System.



Reproduced from Löf, G.O.G., "Solar House Heating," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona, (1955),* Stanford Research Institute, Menlo Park (1956).

Figure 10. Comparison of the Cost of Solar House Heating with Costs of Conventional Heating Systems.

From Figure 10 it is apparent that the heating costs with conventional systems and with systems using partial solar heating are not significantly different.

Löf compared the relative costs of a 512 sq. ft. collector system, a 640 sq. ft. unit, and a conventional natural gas heating system for a house in the Denver area. The costs are shown in Table 2.

Table 2. Computed Equipment and Operating Costs for Heating the 1830 Sq. Ft. Denver House.

	Conventional System	512 sq. ft. Collector	640 sq. ft. Collector
Investment Entire System	$1331	$2010	$2095
Fixed Costs at 5% per year	67	101	105
Fuel Costs (Natural Gas)	53	29	26
Electricity Cost	16	33	33
Total Annual Costs	$ 136	$ 163	$ 164

From these figures, it can be seen that heating with solar energy was somewhat more expensive than heating with natural gas in the Denver area in 1950.

Bliss estimated the cost of a solar operated heating system at $1500 more than the conventional systems. It is his opinion that at the present stage of development, solar heating systems can compete costwise only with the greatest difficulty with conventional systems using fuels at present prices.

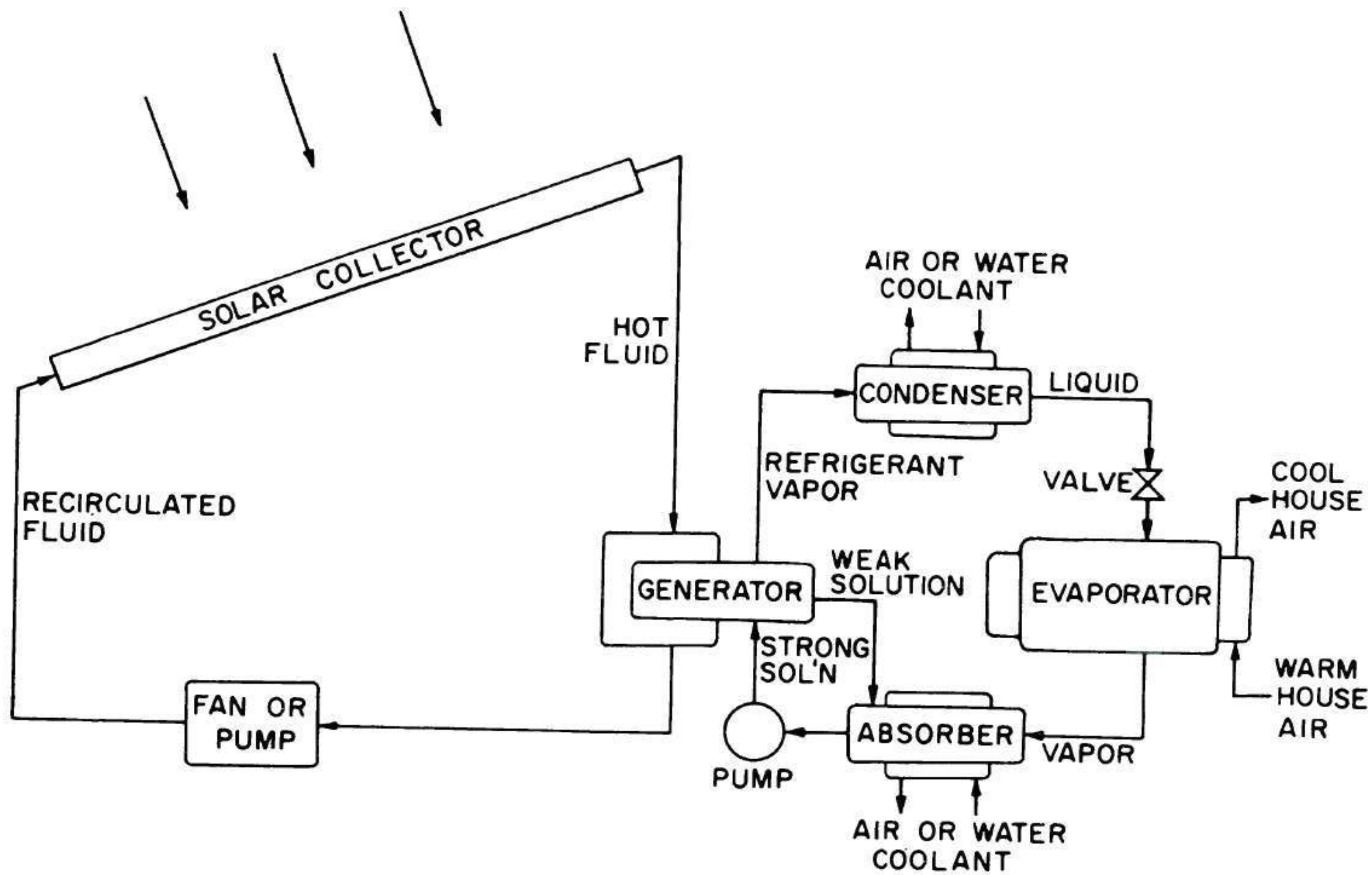
It is concluded that, at the present time, house heating with solar energy is slightly more expensive than heating with conventional fuels. However, it is entirely possible that further developments in solar heating systems or increases in prices of conventional fuels could change the situation in favor of solar heating.

Air Conditioning.--In contrast with solar heating systems, air conditioning by means of solar energy has received very little attention.

At the present time solar energy is being used instead of conventional forms of energy as a source of heat for some air conditioning systems which use absorption refrigeration or absorption dehumidification.

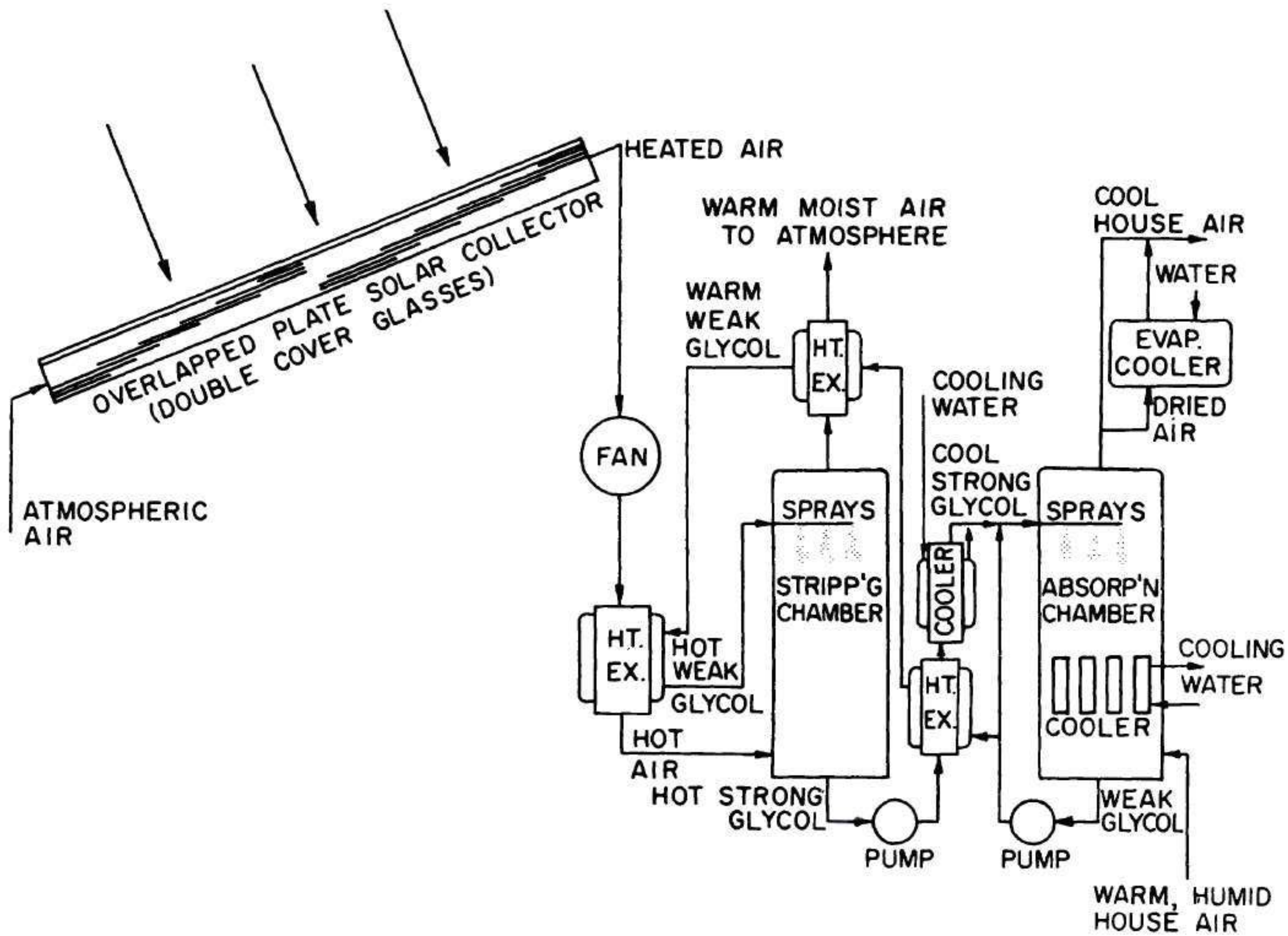
An absorption refrigeration system is shown schematically in Figure 11. Solar heat is supplied to a concentrated solution of ammonia in water. The heat is absorbed by the ammonia which evaporates, leaving a weak ammonia solution behind. The ammonia is then fed to a condenser where it is liquefied. The liquefied ammonia is expanded through a valve to an evaporator where it vaporizes, thereby cooling the space surrounding the evaporator. The cycle is completed with the reabsorption of the ammonia vapor in the weak ammonia solution.

The absorption dehumidifier is used in regions with high summer humidities. In this unit the air is partially dehumidified which makes the air more comfortable. This unit is presented schematically in Figure 12. Warm humid air is contacted with strong ethylene glycol in the absorption chamber. In this unit, the chemical absorbs the moisture from the air. The partially dehumidified air is then supplied to the rooms. The weak ethylene glycol is concentrated in the stripping chamber by contacting it with air heated in a solar collector. The ethylene glycol is recirculated to the absorption chamber. Humidity is thus removed from the



Reproduced from Löf, G.O.G., "Cooling with Solar Energy," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955)*, Stanford Research Institute, Menlo Park (1956).

Figure 11. Absorption Refrigeration Cycle.



Reproduced from Löf, G.O.G., "Cooling with Solar Energy," in *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona (1955)*, Stanford Research Institute, Menlo Park (1956).

Figure 12. Absorption Dehumidification System.

air-conditioned space and discarded into the air stream leaving the top of the stripping chamber.

No complete and thorough cost studies have been reported on either system. Löf (49) indicates that a solar-operated absorption refrigeration system will cost more than a gas-operated unit by the cost of the solar energy collector. He also indicates that the cost of a solar-operated absorption dehumidifier is much higher than the cost of any other type of available domestic air-conditioning equipment.

An estimate of the operating cost of a solar absorption refrigeration system was also made by Löf (50). Based on an investment of $1.00 to $2.00 per square foot of collector area, he estimated the annual cost of depreciation, repairs, and interest at $0.10 to $0.20 per square foot. Taking the efficiency of heat delivery to the absorption refrigerator at 35 per cent of the incident energy, he estimated that one square foot of collector area will deliver about 70,000 BTU to the cooling unit during the cooling season. The cost of this heat delivered to the cooler would be between $1.50 and $3.00 per million BTU. If this cost is compared with $0.50 to $1.00 for natural gas, it is seen that house cooling with solar energy is three times as expensive as cooling with natural gas.

If house heating in the winter is also accomplished with solar energy, the annual heat supplied by a square foot of collector area would be about 250,000 BTU in sunny areas of Central and Southern United States. In this case the heat delivered to the cooling unit in the summer, and to the house rooms in the winter would cost between $0.40 and $0.80 per million BTU, the lower cost being due to the fact that the fixed annual charges are divided over a greater amount of heat collected. This cost also compares with natural gas between $0.50 and $1.00. Thus is some areas of the country, the combined solar cooling and heating system should be competitive with and possibly cheaper than units operated by gas or other fuels.

CHAPTER VII

SOLAR FURNACES

The energy radiated by the sun is dispersed when it reaches the earth, but it is not degraded. Proper concentration of the solar radiation then will give very high temperatures.

In order to concentrate the solar energy, it is necessary to converge the sun's rays either by reflection or refraction.

The use of solar energy to obtain high temperatures is not a development of recent years. In antiquity men experimented with mirrors to reach high temperatures. One of these was Archimedes (287 - 212 BC.). The value of his experiments became evident to his fellow citizens when he broke the siege of Syracuse by the Romans in 214 BC. He accomplished this, according to a description by Galen in De Temperamentis, by setting fire to the enemy fleet with mirrors.

After Archimedes, approximately 1800 years passed before interest in the concentration of solar energy revived. One of the first to renew experimenting was the French scientist Jorge Louis Leclerc Buffon (1707-1788). With a large mirror consisting of 168 plane mirrors of approximately 6 inches by 6 inches he lit a stack of dry wood from a distance of 200 feet (51). He also used his apparatus to melt lead from large distances. On the basis of these experiments he calculated that Archimedes had set fire to the enemy fleet from a distance of 100 to 140 feet (51).

Then a period followed in which solar furnaces became the vogue. Many of these furnaces were built at the courts of kings and princes with which court doctors and other scientists melted gold, silver, and iron to the amazement of courtiers and princesses (52). Lenses were generally used and temperatures up to 2700 degrees F were obtained.

The great French scientist Lavoisier was probably the first to recognize the value of the solar furnace as a research tool. With his furnace consisting of two lenses he was able to reach temperatures of 2700 degrees F.

The first modern solar furnace was built in 1921 by R. Straubel of the Zeiss Company at Jena (53). He used a concave search light mirror with an aperture of 6.5 feet and a focal length of 2.8 feet. Temperatures of approximately 5400 degrees F were attained.

Most of the high temperature furnaces built recently are of this type. They consist of parabolic mirrors that reflect and concentrate the solar radiation at the focus. Usually an arrangement is provided to make it possible to follow the sun on its trajectory. In some furnaces the whole installation, including parabolic surface and focus, is moved with the sun. In others, an auxiliary flat mirror is employed to track the sun and to reflect the rays into the stationary paraboloid. In simpler furnaces the mirror is turned by a clockwork mechanism; the more complicated ones utilize photoelectric cells to actuate suitable motors.

A survey of present solar furnaces was prepared by Cohen and Hiester (54) and by Benveniste (55). The first source lists 23 furnaces in the United States and gives the details of these installations.

Benveniste's tabulation shows four solar furnaces outside the United States. These furnaces are being used for research work for which they are excellent tools, because

(1) The operating temperatures are higher than the temperatures of conventional furnaces,

(2) The temperature can be changed very rapidly in heating and quenching cycles,

(3) There is no contamination by furnace materials,

(4) The solar furnace makes the operation in any desired atmosphere possible over a wide pressure range,

(5) Electro-magnetic fields are eliminated, and

(6) High flexibility is provided for research studies.

In the last few years, many papers have been written describing the design and the construction of these furnaces. The design has been treated by Davies and Cotton (56), by Bliss (57), by Hukuo and Mii (58), and by Hiester, et al. (59).

The design of a heliostat mirror is discussed by Jose (60), the construction of a furnace by Hisada (61), and a guidance system by Moore (62) and Laszlo et al. (63).

A cost study was prepared by Hiester et al. (59). They concluded that for best design a solar furnace should have:

(1) A parabolic concentrator made up of adjustable curved mirror segments,

(2) A fixed concentrator with its axis horizontal, using a heliostat to follow the sun,

(3) A rim angle between 50 to 70 degrees, and

(4) A reflecting surface of back-silvered glass.

In this study they included the cost of a furnace with an aperture of 100 feet. This cost was estimated at $863,000, completely erected. The result for the 100 foot furnace was extrapolated to approximate costs for furnaces with 50 to 200 foot concentrators.

Another estimate was prepared by the Frenchman Trombe (64), for a 177 ft. solar furnace to be built at Mont Louis. The cost of this furnace was estimated at 300 million francs or approximately \$840,000. The lower cost is probably due to the lower labor rates in Europe.

An actual construction cost of a furnace built at Mont Louis with an aperture of 35 foot is reported as \$60,000 (65).

These figures show that the cost of a solar furnace at the present is high, but it appears that by minimizing the heat losses an improved solar furnace can be built at a lower cost. However, in spite of the high cost, it is probable that many solar furnaces will be constructed in the near future as the industrial requirements for high temperature materials become more pressing.

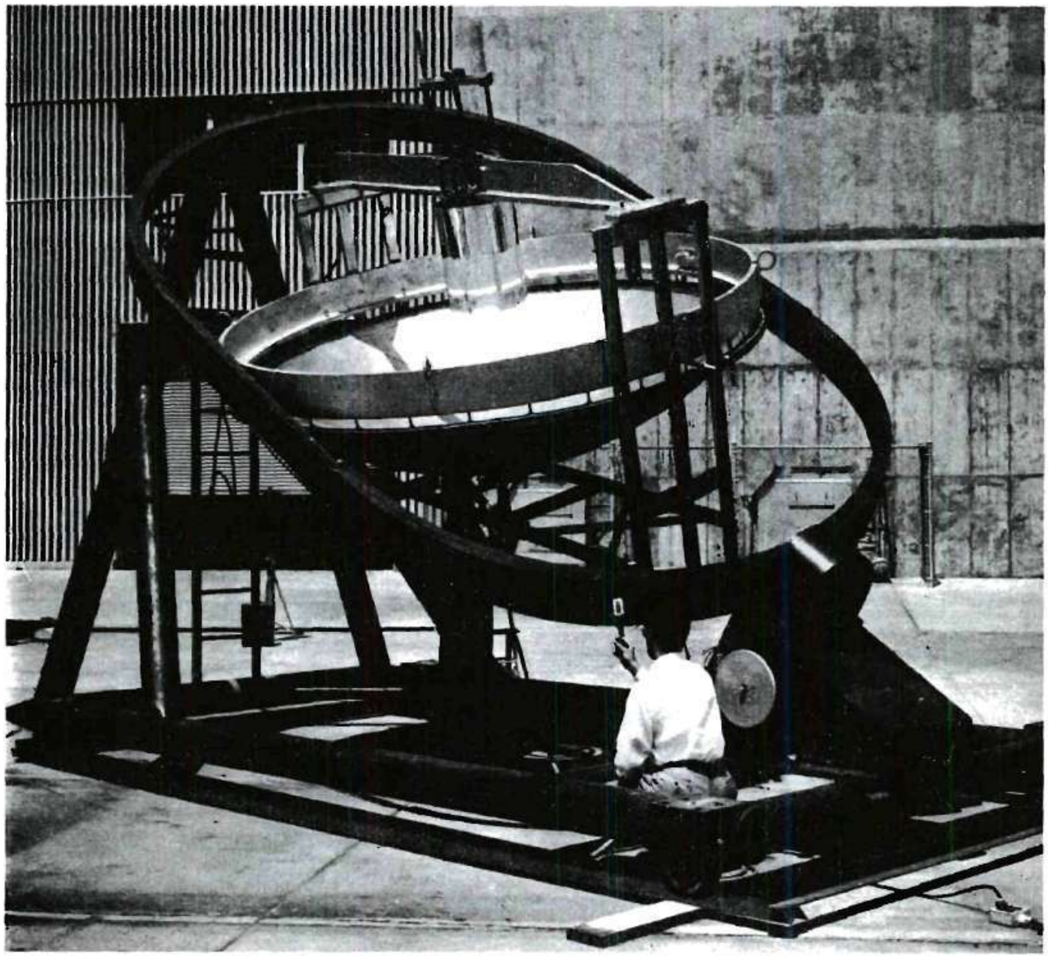


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Figure 13. Solar Furnace.

CHAPTER VIII

SOLAR COOKERS

The development of the solar cooker started at the end of the eighteenth century with the work of de Saussure in Switzerland, Herschel in England, and Mouchot in France.

Since that time many solar stoves have been designed and built. All of these can be classified into three groups:

(a) Reflector type cooker,

(b) Insulated box type cooker, and

(c) Indirect cooker.

The reflector type cooker is the most common. It consists of a parabolic or spherical reflector that concentrates the solar radiation on a cooking vessel. A cooker of this type was designed recently by scientists of the National Physical Laboratory in New Delhi for distribution in underdeveloped countries, especially India. The 10 sq. ft. aluminum reflector produces about 350 watts at noon. The cooker is presently mass produced by Davidayal Metal Industries Ltd. in Bombay.

One of the disadvantages of this cooker is its cost; it represents a fairly large investment for an Indian farmer.

In a study aimed at lowering the cost, Duffie (66) investigated several cookers. His cheapest design has a stationary soil-cement reflector. This reflector can be formed in the soil by swinging a blade fastened to a stationary point. After generation of the rough shape, a shallow layer of a mixture of soil and cement is placed in the depression and smoothed with the blade. After setting, a reflective lining of aluminized Mylar pressure sensitive tape is applied. The cost of materials for a 600 watt cooker was estimated by him at $5.25. The time to prepare one of the soil-cement cookers was placed at 4 man-hours. A disadvantage of this design is its lack of mobility. Consequently the cooker can be used only during a limited period of the day.

Another reflector type cooker was designed by Duffie. This cooker consists essentially of a plastic shell with a metalized lining. This is probably the most practical and most promising design. The cooker is portable and can be turned to follow the east-west motion of the sun. The materials to construct this cooker cost $9.20. The estimated time of construction is 10 man-hours.

The insulated box-type cooker consists of an insulated box, painted black on the inside, covered with one or more glass panes to admit the solar radiation. These cookers were investigated by Telkes (67). The temperature attained was approximately 300 degrees F, which is too low for practical cooking operations.

Telkes found that the operating temperature could be increased with plane mirrors forming a 60 degree angle with the plane of the absorber. With those plane concentrators, temperatures up to 440 degrees F were attained, and the usual cooking operations could be carried out without difficulty.

A cooker of the indirect type was constructed by Abbot (68). This cooker has provisions for storage of heat so that meals can be cooked after dark. The cylindrical reflector of parabolic cross-section focuses the solar rays upon a black copper tube containing a high boiling fluid. The fluid inside the tube is heated and rises to the top of a reservoir. The cooler fluid at the bottom of this reservoir flows to the tube in the focus of the mirror where it is heated. In this manner, a continuous circulation of hot fluid is maintained. The hot fluid can be used to heat an oven whenever needed.

In order to reach high temperatures, the reservoir and the pipes were insulated with fire-brick. The blackened heater tube was insulated with two concentric glass tubes with a vacuum between. Temperatures up to 400 degrees F were attained with engine oil as the heating fluid. The temperature of the oven long remained high so that many kinds of food could be cooked, even at night.

The reflector type cooker is considered the most promising of the several designs due to its simplicity and low construction cost. The main market of these cookers is in the non-industrialized areas where fuel for cooking purposes is not readily available. However, the cost of the cookers must be lowered appreciably before their use becomes widespread.

CHAPTER IX

DIRECT CONVERSION OF SOLAR ENERGY INTO ELECTRICAL ENERGY

For several decades, scientists have worked on the problem of converting solar radiation directly into electrical energy. This work resulted in three devices for converting solar energy into electrical power: the thermopile, the photogalvanic cell, and the photovoltaic cell.

The thermopile is a discovery of Seebeck who found that a current is produced in a circuit consisting of two dissimilar metals when the junctions are held at different temperatures. The necessary energy to maintain the current is obtained from the heat supplied to the junctions. By heating one junction with solar radiation, the solar energy is directly converted into electricity.

Thermopiles are generally made of the following materials:

(1) Chromel-P and constantan,

(2) ZnSb with small amounts of impurities (Sn, Bi, Ag, etc.) and constantan, and

(3) ZnSb (Sn, Bi, Ag, etc.) and 91 Bi-9 Sb.

Telkes (69) has summarized the efficiencies of thermopiles by stating that up to 1 per cent of the incident solar energy can be converted into electricity without concentration of the sun's rays, and that an efficiency of 3.35 per cent is possible with concentration of the solar energy.

The photogalvanic cell consists of two electrodes immersed in electrolytes or an organic liquid. Light striking one of the electrodes produces photochemical changes in the electrolyte which are usually oxidation-reduction, i.e., transfer of electrons. The reaction which takes the oxidation and reduction products back to their original states can be utilized to obtain electrical work by providing an external circuit between the electrode in contact with the oxidation products and the electrode in the reduced solution. The electrons flowing from the reduction product through the circuit and into the oxidation product provide the electricity.

Sancier (70) lists four types of photogalvanic cells:

(1) Metal electrodes immersed in solutions of electrolytes,

(2) Metal electrodes coated with inorganic compounds immersed in solutions of electrolytes,

(3) Metal electrodes coated with a dye and immersed in solutions of electrolytes, and

(4) Metal electrodes immersed in organic liquids.

He states cautiously that photogalvanic cells of type 2 and 3, metal electrodes coated with inorganic compounds and those coated with dyes immersed in solutions of electrolytes, are most favorable for use as a cyclic solar battery.

The highest efficiency obtained from this type of cell is somewhat less than 1 per cent (71). However, other photogalvanic systems might be found that operate at higher efficiencies. For more information a review of photogalvanic systems by Copeland _et al._ (72) may be consulted.

The photovoltaic cell is a solid state device which was developed around 1876. In this device, light falling on a light sensitive material detaches electrons completely from their parent atoms. These liberated electrons flow as an electric current, so that light is transformed directly into electricity.

At the present time, these photocells are widely used in photographic exposure meters, photo-switches, and photoelectric eyes. In these devices selenium is used as the light sensitive material. Efficiencies are about 0.6 per cent when operated in direct sunlight (71).

In 1954, scientists of the Bell Telephone Laboratories raised the efficiency of the photovoltaic cell to about 6 per cent. Later development work has raised the efficiency still further to 11 per cent so that now 11 per cent of the intercepted solar energy can be converted into electricity. This is an enormous increase if it is considered that the maximum efficiency is 22 per cent (73). This maximum limit on the conversion of solar energy into electricity is imposed by the minimum energy required to produce a positive and a negative charge, which is 1.1 electron volts in silicon (74). Thus, only photons with a wavelength shorter than 1.1 micron have enough energy to produce electricity in a silicon solar battery. Of the energy carried by these photons only 1.1 electron volts is used to produce current, the extra energy carried is dissipated as heat. Based on these considerations, a maximum efficiency of 22 per cent was calculated.

The heart of the solar cell is the p-n junction at the front surface of a plate of silicon. When light hits a silicon crystal, the photons with sufficient energy liberate a negative charge and a positive charge. Due to the strong electric field at the p-n junction, the electrons are kept on the n-side and the holes (positive charges) on the p-side. This behavior is shown in Figure 14. The accumulation of different charges on both sides of the p-n junction creates a voltage difference between the ends of the crystal.

The fabrication of a p-n junction was described by Pearson (75). Approximately one part of arsenic is melted with a million parts of extremely pure silicon, and a large single crystal ingot is formed. This crystal is cut into thin wafers that are placed in a quartz tube containing vapors of a boron compound. The assembly is then heated to a temperature between 1000 and 1200 degrees C and held for a specified time. In this time a p-type skin is formed on the n-type silicon. After cooling, the p-type layer is removed from the back surface and lead wires are connected to the p-layer on the front surface and the back of the slab that is n-type.

Experimental evaluation of the solar cell showed that the maximum power output is about 11 milliwatts per sq. cm. at an output of 0.45 volt. Under these operating conditions 11 per cent of the solar energy intercepted was converted into electrical energy (76).

The first experimental application of the silicon battery was as a power source for operating a type p rural carrier amplifier at Americus, Georgia. The solar cell was installed at the top of a telephone pole. This primary power source charged a 22-volt nickel-cadmium storage battery which in turn powered the all-transistor amplifier. A few hours of sunlight per day were sufficient for continuous operation of the amplifier.

Although the efficiency of the new photovoltaic cell is at least an order of magnitude greater than the best previous devices, it is still

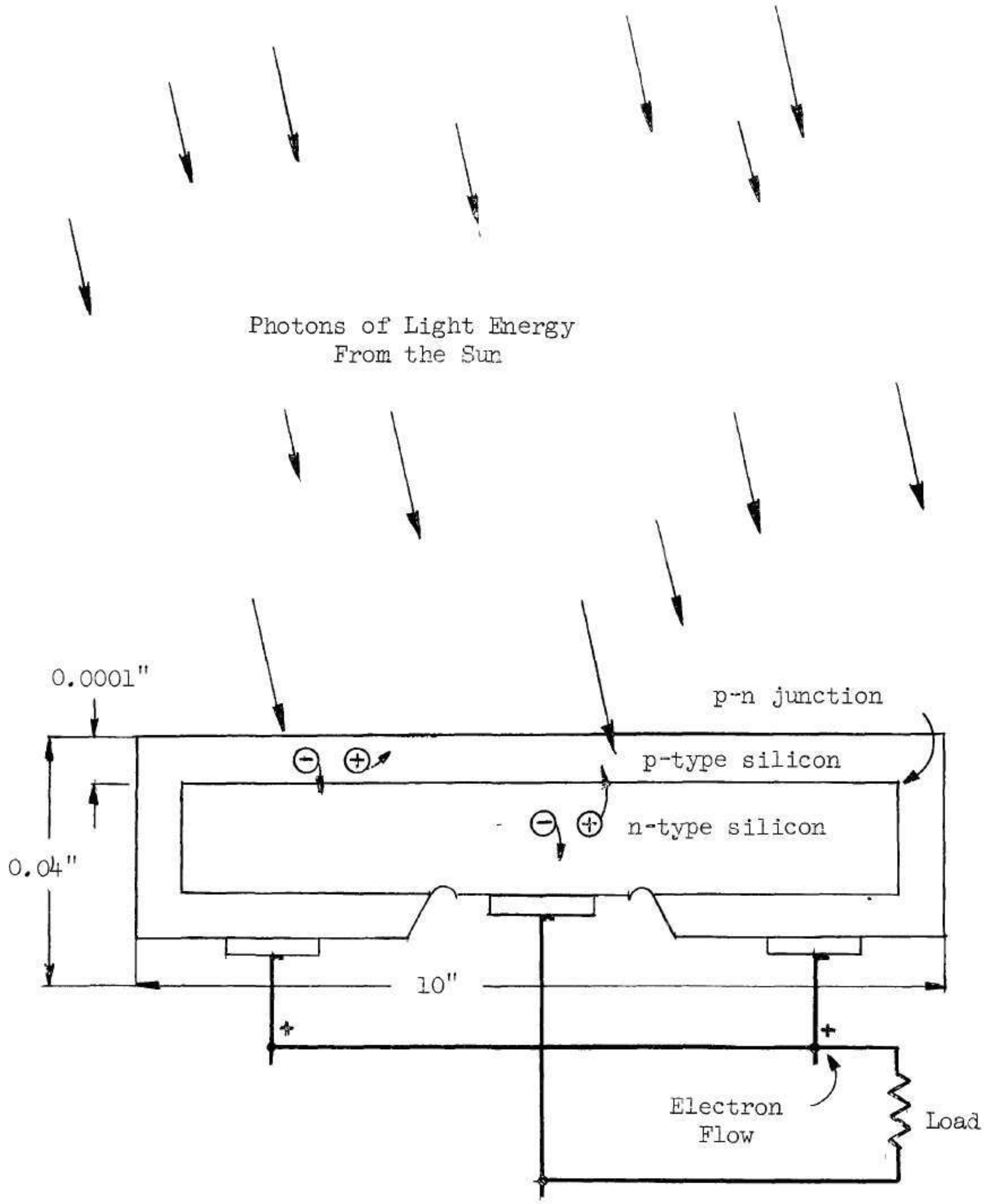


Figure 14. P-N Junction in a Silicon Crystal.

too expensive to compete with more conventional power generators. However, it might be used for special applications, such as supplying electricity for recording instruments in observatory cabins in remote regions far away from any other electricity supply. The high price of the cells, however, prohibits their large scale use at the present time.

CHAPTER X

PHOTOSYNTHESIS

Photosynthesis is the name of the process occurring in plants by which carbohydrates are formed from carbon dioxide and water under the influence of sunlight. In this process a fraction of the solar radiation is absorbed by the plants and converted into chemical energy.

Photosynthesis is a very common reaction. It has been estimated that the rate of carbon fixation on earth is 15 to 20 x 10^{10} tons annually (77). At the same time, it is the most important reaction since it is the source of all our food and fuel.

The process can be described by the following reaction equation:

$$6\ CO_2 + 6\ H_2O + \text{Energy} \overset{\text{Chlorophyll}}{=} C_6H_{12}O_6 + 6\ O_2$$

carbon dioxide	water	sunlight	carbo hydrates	oxygen

The actual process which takes place is not yet completely understood. However, it is known that light produces the following reactions in the plant. The light energy is absorbed by the yellow-green pigment of the plant, the chlorophyll. This energy is then utilized by the chloroplast, the semi-liquid material in the plant cell, to decompose water into hydrogen and oxygen. The active hydrogen, produced in this manner, is brought into contact with carbon dioxide and reacts with it to form carbohydrates that contain the absorbed energy.

In 1955 an important break-through occurred in this field of investigation when a group of scientists succeeded in extracting the chloroplast from plant cells without damage to the chloroplast. This material was then used to make carbohydrates from water and carbon dioxide in a test tube. This was a direct chemical synthesis without the help of living plants.

Laboratory investigations were made to determine the minimum energy necessary for fixing a carbon atom in the photosynthetic process. Daniels (78) indicates that this energy is 320 kilocalories per gram atom of carbon. One gram atom of carbon evolves 112 kilocalories on burning to CO_2. The efficiency of photosynthesis is therefore of the order of $\frac{112}{320}$ or 35 per cent. This is the maximum efficiency that can be realized under the most favorable conditions of weak light and an ample supply of carbon dioxide.

It is well known that the photosynthetic efficiencies of ordinary plants are very much lower. The following efficiencies were reported in the literature: Potatoes 2.62%, corn 3.3%, and turnips only 1.84% (79). There are many reasons for this low efficiency (80):

(a) Only visible light, which forms 50 per cent of the sunlight, can be used in the photosynthetic process,

(b) The growing season lasts for only a third of the year,

(c) The ground is covered with green leaves for only part of the growing season,

(d) The concentration of the carbon dioxide in the air is very low, and

(e) The sunlight is much too bright for maximum efficiency.

Research is presently being conducted on increasing the efficiency of the photosynthetic process, with the aim of producing more food and fuel. Among the research projects, those stand out which are based on intensive cultivation of fresh water algae. These micro-organisms contain chlorophyll and are able to convert carbon dioxide and water into organic compounds under the influence of light energy.

Algae, in large cultures under sunlight illumination, have efficiencies in the same range as ordinary plants (81) under optimum conditions. However, the yields per acre are much higher because the concentration of the nutrients is easily controllable and light losses due to incomplete coverage of the exposed area either in time or in space can be avoided (81). Due to these factors an average yield of 30 to 35 tons of dry material per acre-year has been obtained in pilot plants under natural illumination (82). This yield compares very favorably with yields of ordinary crops reported as 2 tons of dry organic material per acre-year (83).

The equipment for producing algae is simple. It consists of:

(a) A container with a transparent top plate,

(b) Equipment to circulate the culture in the container,

(c) Equipment to harvest the algae, and

(d) Storage facilities.

Mass cultures of algae can be grown in media prepared from fresh water in which the nutrient elements are dissolved. However, algae grow extremely well in industrial wastes (84). This seems to be the most economical way to grow algae.

In this process, bacteria and algae are grown simultaneously in shallow ponds or tanks. The bacteria normally present in municipal wastes decompose some of the organic matter with the release of carbon dioxide, methane, ammonia, and micronutrients. In the presence of light, the algae use these nutrients and produce the oxygen needed by the aerobic bacteria to continue oxidizing the organic matter making more nutrients available for the algae.

The algae grown on wastes from cities contain 45 - 60% protein, 10 - 20% fat, 15 - 25% carbohydrates, and 10 - 20% ash on a dry weight basis (82).

The algae can be harvested by pumping the culture through a filter or a centrifuge. The algae can then be dried and utilized as food, or the slurry can be transferred to an anaerobic fermenting unit to convert the organic matter into methane and hydrogen.

The food value of algae was determined in experiments with young albino rats (85) and ducks (86). It was found that the protein is of astonishingly high quality and not only equal to animal milk protein or egg white protein but superior since it contains substances that can prevent and cure liver necrosis in animals.

To produce fuel from the algae sludge, a fermenting unit is employed. The conversion into methane can be carried out at 99 per cent efficiency with pure cultures of some methane fermenting bacteria, but the rates of conversion exhibited by single species are too slow (87). Commercial practice today obtains much more rapid rates by using mixed cultures of unknown species, but high losses occur in the conversion step so that only 60 to 80 per cent of the heating value is likely to be utilized.

The gas evolved is expected to have a composition of 50 - 70%

methane, 20 - 30% carbon dioxide, 2 - 10% hydrogen, and 1 - 3% hydrogen sulfide (88). The methane may be liquefied and shipped in that form, the carbon dioxide may be reintroduced into the algal culture during periods of maximum light intensity. The remaining solution that contains nitrogen and phosphates may be used for irrigation purposes.

Liquid fuels in the gasoline and kerosene range can be produced from the algae by reacting the methane and the carbon dioxide evolved in the fermenting unit in a variation of the Fischer-Tropsch synthesis. A yield of 35 tons per acre-year reduces to 6 - 9 tons of liquid hydrocarbons after providing for pumping and fuel requirements (88).

The economics of growing algae to produce food and fuel was investigated by Fischer (89). Based on pilot-plant information, he estimated the investment and the operating cost for a plant covering 100 acres of total area with 62 1/2 acres of exposed culture. Table 3 summarizes the fixed capital investment for the installation.

Table 3. Investment in a 100-Acre Algal-Culture Installation

(Assumed average production - 12,500 pounds per day)

Area preparation and growth tubes	$220,000
Circulation equipment, installed	440,000
Cooling facilities, installed	1,180,000
Preharvest equipment, installed	240,000
Central harvesting equipment, installed	234,000
Gas preparation and distribution system, installed	161,000
General facilities, equipment and buildings	211,000
Engineering and contingencies	534,000
Total	$3,220,000

This estimate indicates that the investment is over $30,000 per acre.

An operating cost of $0.25 per pound is shown in Table 4.

Table 4. Operating Cost for a 100-Acre Algal-Culture Installation

(Assumed average production - 12,500 pounds per day)

	Cost per day
Labor, supervision, and plant overhead	$950
Utilities and supplies	360
Replacement of growth tubes	410
Insurance and taxes	460
Depreciation	920
Total	$3,100
Approximate cost per pound	$ 0.25

The price of competitive nutritive materials today is 10 cents per pound or less; this puts algae out of consideration for the present, at least in the United States. However, in less developed countries where protein food must be imported, the production might be economical since lower labor rates would lower the investment and the operating cost.

It appears, however, that further research and development work could lower the cost. Fischer (89) estimated that the cost might be brought down to 5 - 10 cents per pound of dry algae which would make the production economically attractive.

The production of fuel from algae is feasible technically, but it does not appear attractive at this time. Fuel obtained in this manner would cost at least 10 cents per pound. The equivalent amount of coal would be about 0.8 pound, which at the present would cost about 1/2 to 3/4 cent.

CHAPTER XI

SOLAR ENERGY AND SPACE TRAVEL

Approximately four years ago the human race entered the Space Age with the launchings of Sputnik I, on October 4, 1957, and Explorer I, on January 31, 1958. In the following years many more rockets and satellites have been shot into space to obtain valuable data in the universe surrounding the earth.

To provide the necessary energy for measuring instruments and radio transmitters large amounts of electricity are needed. In the first few satellites storage batteries supplied the electrical power. However, they were not too satisfactory because of their short life. It was clear that better power sources had to be found before measurements further out in space could be made.

Faced with this problem, our engineers and scientists adapted the photovoltaic cell for use in space and used them for the first time to power one of the radios of Vanguard I. These solar cells proved to be satisfactory and reliable, and many satellites have since been equipped with these devices. One of the satellites, Tiros I, was completely covered with 9,200 of these cells (90). Another, Pioneer V, had four vanes studded with 1,200 solar cells each (91).

Although failures during launchings are the rule rather than the exception at the present, and space travel is probably still a long time off, it is time to start thinking how the needs of the future space traveler can be satisfied and how the power to drive the space ship can be obtained.

The space traveler must be provided with food and oxygen, in amounts of 3,000 kilocalories and 1 kilogram daily. The food could be supplied in a concentrated form. A product like this has already been developed by the National Research and Development Corporation. It is a combination of cellulose gum (a bulk providing base), carbohydrates, fats, proteins, minerals, and vitamins in sufficient quantity to meet the basic daily requirements. The oxygen could be stored in the liquid form under pressure. After exhalation the air could either be ejected or purified for future re-use. In either case the weight of the total amount of oxygen or the weight of the purification equipment would be very high.

Fortunately, a much easier method is available to provide the food and the oxygen. Leafy plants and chlorella algae have been found to produce relatively large amounts of oxygen in the process of their photosynthesis. In this process the carbon dioxide is removed from the air and replaced by oxygen. Algae are also highly nutritive and can be consumed as food. It is estimated by Bowman (92) that 200 liters of algae culture per man would be needed to produce the required amount of food and to purify the air.

To sustain the photosynthetic process the algae need a medium containing the nutrients, especially nitrogen which is usually added in the form of ammonium or potassium nitrates. The energy required in the process is derived from sunlight. Bowman (92) proposed the use of human excretions as a readily usable source of nitrogen. He mentions that there are about 20 grams per day of urea in urine and that the feces contain 5 to 10 per cent of more complex nitrogen compounds. However, feces are extremely high in bacteria which might be detrimental to algae growth. For this reason he proposes to feed the raw material consisting of water, urine, and feces through an ultraviolet irradiation system to kill the bulk of these bacteria. It also appears desirable to desalt the urine because an excess of salt in the culture medium might kill the algae. This desaltation, however, can be accomplished very easily in an ion exchange resin. Admittedly, the aesthetic aspect of the cycle is less than ideal, but this is largely because it is a direct and immediate simplification of the process that goes on in a more subtle way in nature.

The space traveler must also be supplied with adequate electrical energy for his measuring instruments, radio receivers and transmitters, and for cooking purposes. Cooley (93) reports that a manned satellite with two to five men would require a minimum power of 800 watts and a maximum power of 5 to 10 kilowatts.

One large potential source of electricity would be an atomic reactor in conjunction with an electric generator. However, the atomic pile with moderator, heat exchangers, and radiation shields would add considerably to the weight of the space vehicle. Because of this and the radiation hazards, nuclear power generators for space vehicles are not just around the corner.

The vast amount of solar energy in space suggests it as a source of power. At the present time three systems of converting solar radiation into electric power appear to be promising. These systems will be discussed very briefly.

In one system, the solar radiation is converted directly into electricity in photovoltaic cells, commonly called solar cells. This system is presently being used mainly because the solar cells can be easily incorporated into the design of a satellite. One drawback to the extensive use of these units at the present time is the high cost of the cells, approximately $125 per watt (94).

In the second system, the conversion of solar radiation into electricity is accomplished by using the solar energy to heat a compressed gas in a channel shaped mirror. The gas expands in a turbine that drives an electric generator. The gas is cooled by passing it through a tube on the shadow side of the satellite and is returned to storage.

In the third system, a concave mirror concentrates sunlight on a boiler having the side exposed to the sun black and rough. The side away from the mirror and receiving no heat has a reflecting surface as protection against heat losses. The steam produced in this manner is utilized to operate a generator. The exhaust steam is cooled in the shadow and is returned to the boiler. Due to the relatively low overall efficiencies of steam engines, which are of the order of 10 per cent, it is necessary to collect the solar radiation over a large area.

To propel the space vehicle some type of engine is required. In this engine the propellant mass is accelerated by heat or electrical energy after which it is ejected from the vehicle. The ejected mass provides the thrust to propel the space ship according to the principles stated in Newton's laws of motion.

In the present types of rocket engines propulsion is achieved by ejection of a gas produced by chemical reactions. The gas is accelerated by the heat energy generated during the reaction and very high thrusts are developed. Unfortunately, the "fuel" consumption is extremely high. This seriously limits such a propulsion system for extensive journeys into space.

A second method of propulsion involves the acceleration of a gas by heat energy from nuclear reactors or from solar radiation. The gas used is hydrogen that is heated to temperatures of the order of 3,000 to 4,000 degrees K. The heated hydrogen expands in the rocket nozzle attaining a tremendous speed. This system is presently under study by the National Aeronautics and Space Administration.

The third propulsion system is electrical. The propellant is vaporized and ionized on numerous incandescent platinum surfaces. Both rubidium and cesium have been proposed as propellants due to their low heats of ionization. The ions produced on the hot surfaces are accelerated by electric fields and are ejected into space, thereby providing the necessary thrust. To ensure that the space ship remains uncharged, the electrons are emitted from heated cathodes to compensate for the discharge of ions.

Large amounts of electrical power will be needed in this propulsion system. This power can be derived from solar energy or an atomic reactor as described above.

The thrust produced by the ion rocket engine is very weak; consequently the acceleration of the space ship is extremely slow. For this reason, these ships will not be able to start from the earth because the thrust required for this purpose has to be greater than the take-off weight. Therefore these engines could be used only in true deep-space vessels that spent their entire time moving from planet to planet. They could only orbit their destination and never descend to its surface.

The acceleration of an ion rocket will be of the order of a milli-gravity or kilometer per second per day. This relatively slow acceleration will make possible the construction of large power producing parabolic mirrors, since the stresses on these mirrors would be very small. Calculations made by Stuhlinger (95) show that the slow acceleration is not a serious handicap. His calculations indicate that an electrically driven space ship with a pay load of 50 tons and a total initial mass of 250 tons can cover a distance of 183 million kilometers within a year.

The fourth and last propulsion system makes use of the radiation pressure in space. Garwin (96) stated that the pressure exerted by the solar radiation could be used to propel a space vehicle. Computations made by him, based on the use of a 0.1 mil thick plastic sail, show that it is perfectly feasible to use the pressure of the radiant energy from the sun to move around in space.

CHAPTER XII

DISCUSSION

In our present mechanized world tremendous amounts of energy are consumed daily. All the energy that is presently being used -- whether from petroleum, natural gas, coal, or waterfall -- came from the sun. Also, man is completely dependent upon the sun for his food and oxygen produced by the process of photosynthesis.

In prehistoric times the drain on the energy reserves was very small. Prehistoric man probably used some wood to keep warm and to cook his meals. For power he depended solely on his muscles. With the small population that then existed the energy consumption must have been negligible compared with the supply.

As the population increased, the energy requirements grew, but the demand never approached the renewable supply of wood until the beginning of the nineteenth century. By this time James Watt had developed the steam engine and the industrial revolution had begun. Energy requirements skyrocketed and whole forests were depleted during the early part of the century just to supply wood for the new machinery.

Man realized then that other energy sources had to be developed and he started to tap the non-renewable coal and oil reserves on an ever-increasing scale. Through technological improvements in the recovery of fuels, production has kept pace with the energy demand.

In the years ahead, it appears that the energy demand will grow even more because the non-industrialized part of the world will start consuming energy at a much higher rate than before. Also the growing populations of the industrialized countries will demand more and more energy.

How long will our fuel supplies last? is a question which cannot be answered very easily. It requires a study of the available reserves, the population growth, and the increase in the per capita demand of energy.

The available reserves of fossil fuels were studied by Putnam (97), and Ayres (98). Putnam estimated the economically recoverable reserves, i.e. the fuels that can be produced at less than twice 1950 costs. His estimate of the reserves in the United States is presented in Table 5; the estimate of the world reserves is shown in Table 6.

Table 5. Fossil-Fuel Reserves in the United States Recoverable at Costs Less than Twice 1950 Costs

Fuel	Heat Content Q*
Coal	6.0
Oil-Gas	0.5
Oil from Shale	0.4
Total	6.9

* 1 Q = 10^{18} BTU

Table 6. Fossil-Fuel Reserves in the World Recoverable at Costs Less than Twice 1950 Costs

Fuel	Heat Content Q
Coal	32.0
Oil-Gas	5.0
Oil from Shale	1.0
Total	38.0

Ayres estimated the minimum and maximum fuel reserves. His minimum values are in close agreement with Putnam's values of the economically recoverable reserves. His maximum values are shown in Tables 7 and 8.

Table 7. Ultimate Reserves of Energy from Fossil-Fuel Deposits in the United States

Fuel	Heat Content Q
Coal	56.0
Petroleum	0.6
Natural Gas	0.4
Oil from Shale	2.2
Total	59.2

Table 8. Ultimate Reserves of Energy
from Fossil-Fuel Deposits
in the World

Fuel	Heat Content Q
Coal	191.0
Petroleum	1.3
Natural Gas	0.8
Oil from Shale	3.3
Total	196.4

The population growth must be estimated too. In 10,000 B.C., the population of the earth must have amounted to about a million persons. The increase followed a regular pattern until the seventeenth century when the growth of the population became explosive both in China and the West. By 1950 the world population had reached the 2.4 billion mark and the population of the United States had increased to 150.5 millions (99). Thus far our figures were based on facts. But now it becomes necessary to predict the growth of the population. This can only provide approximate figures since many factors are unknown at the present time.

The estimate will be based on the known rates of increase of the six population groups into which the world population is divided. These groups and the rates of increase are shown in Table 9.

In our estimates, the rates of growth were assumed to remain constant because of the following considerations.

Table 9. Status of the World Population Groups in 1947 (100)

Group	I	II	III	IV	V	VI
Countries	N. W. Europe Central Europe	United States Canada Australia New Zealand So. Europe the Netherlands	U. S. S. R. Cuba Un. So. Africa E. & S.E. Europe Japan Colombia Brazil Argentine Siam Fr. No. Africa	Rest So. America Central America Korea Ceylon Mid. East S. W. & S.E. Asia	Indonesia Egypt India Pakistan	China Rest of Africa
Populations in 1947 - millions	225	271	441	283	528	580
Rate of Annual Increase - %	0.7	1.2	1.6	2.0	1.3	0.5

The mortality of the populations in groups I and II is already very low. But it appears that it might become slightly lower when cures are found for cancer and coronary diseases. The birth rate has stabilized in the last decade and is expected to remain stable. For these reasons the rate of growth is expected to remain fairly constant.

Of the countries in group III, Russia has a pro-natalist policy. Putnam (101) mentions that a woman who bears 10 children receives the title Heroine Mother of the U.S.S.R. Therefore, with this emphasis on productivity, an increase in the rate of growth can be expected for this country. The other countries in this group are expected to modernize their public health measures which will decrease the mortality rate. However, birth control programs are assumed to level this out. Therefore, it appears that the rate of natural increase will remain fairly constant or increase slightly at the most.

Groups IV, V, and VI are comprised of the underdeveloped countries where famines and other disasters have been the rule rather than exception. If anything, we can expect drastic reduction of the death rate from malaria, cholera, plague, and infant and maternal mortality (102). It appears that birth control programs will not be able to keep the populations in check. But, conservatively the rate of growth has been assumed to remain constant.

Based on these assumptions, the populations in each group were calculated for 1975, 2000, 2025, and 2050 AD to arrive at the world population in these years. The results are presented in Table 10, and in Figure 15.

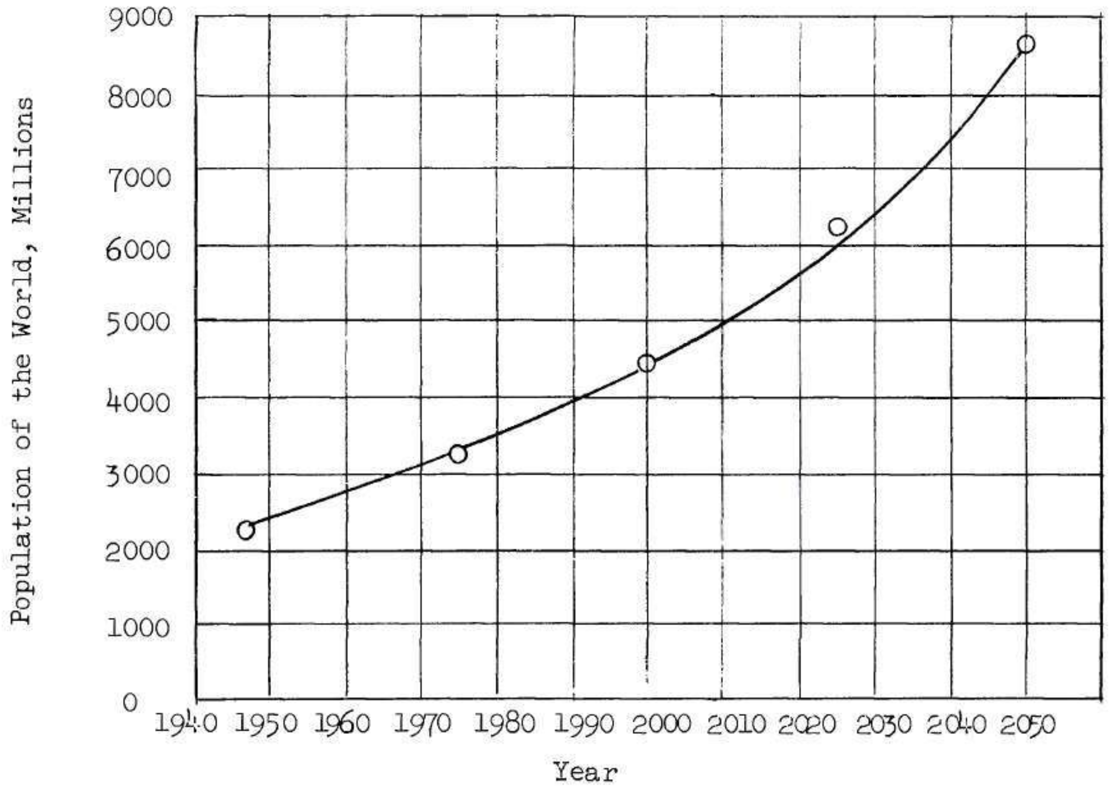
Table 10. Estimated Population of Each World Group

World Group	Population Millions			
	1975	2000	2025	2050 AD
I	274	324	388	461
II	379	510	686	925
III	687	1,020	1,520	2,260
IV	493	810	1,328	2,180
V	760	1,050	1,450	2,000
VI	666	756	856	970
Total World Population	3,259	4,470	6,228	8,796

The population of the United States was estimated separately. The results of our calculations -- based on a population of 150.5 million in 1950 and a rate of increase of 1.2 per cent annually -- are presented in Table 11 and also in Figure 15.

Table 11. Estimated Population of the United States in 1975, 2000, 2025, and 2050 AD.

Year	Population Millions
1950	150.5
1975	202
2000	273
2025	369
2050	496



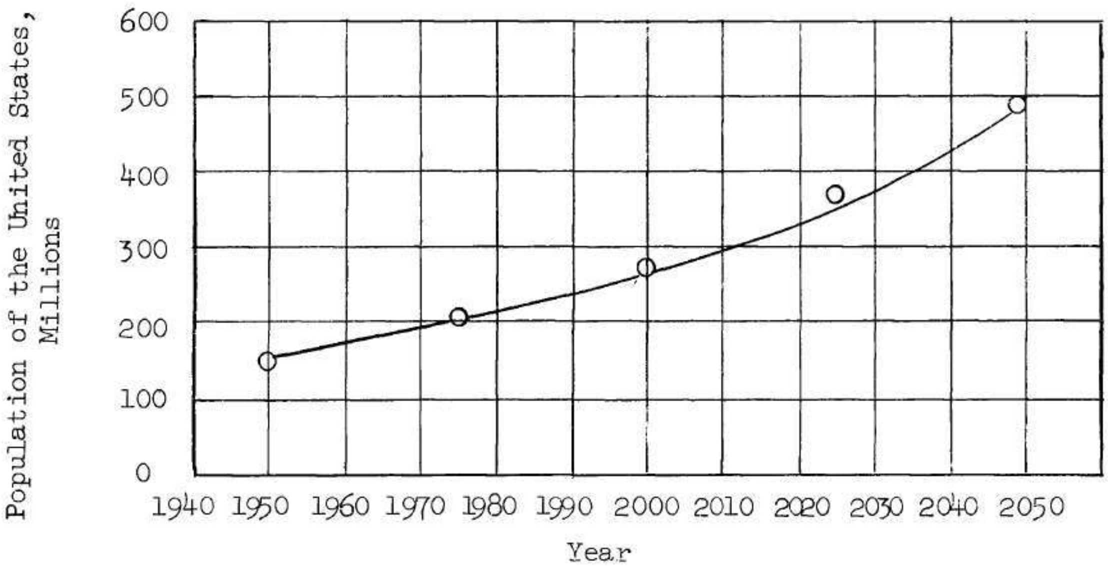


Figure 15. Estimated Population of the
World and the United States.

The estimates indicate that the world population will increase to approximately 8.5 billion by 2050 A.D.; the population of the United States will then amount to 496 million.

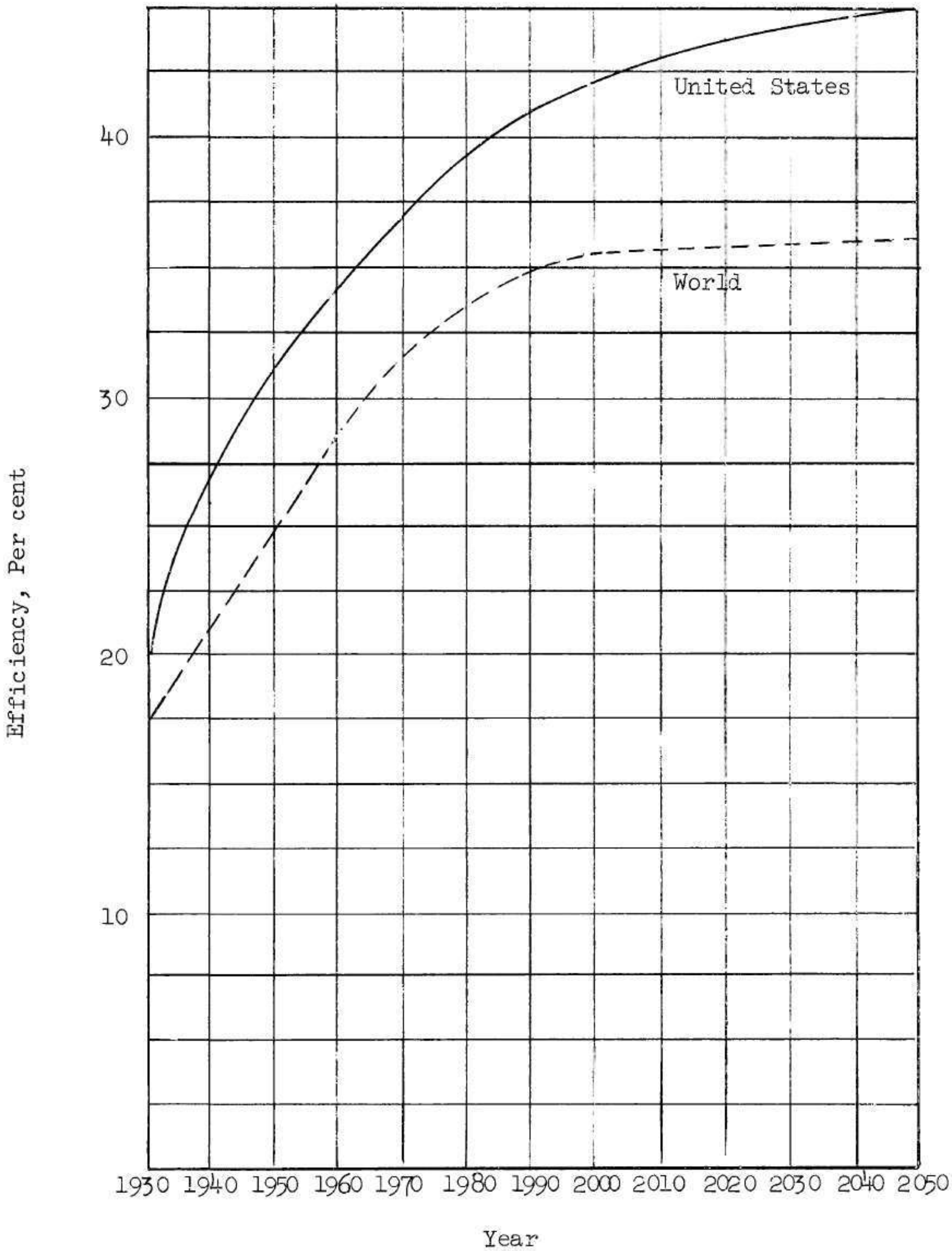
One final step in the estimation of the life of the fuel reserves remains. This step is the calculation of the annual energy demand. The energy consumption can then be obtained by dividing the energy demand by the estimated efficiency as presented in Figure 16 (103).

The most probable rate of growth of the per capita demand of energy is expected to be not less than 3 per cent annually for the World as a whole (104). The per capita demand in the United States is expected to increase by 3 per cent annually until 1980, and thereafter by 1.5 per cent (105). Based on these assumptions and the estimated population increase, the total annual energy consumption of the World and the United States was calculated. The results of these computations are presented in Tables 12 and 13 and in Figure 17.

From these data the cumulative energy consumptions of the World and the United States were calculated. These results are presented in Tables 14 and 15, and graphically in Figure 18.

Figure 18 shows that the world energy consumption has been 13 Q up to 1950. Starting at 1950 the energy consumption will increase to 26 Q in 2,000 AD. In other words, as much energy will be consumed in these fifty years as was consumed in all the years before 1950. The economically recoverable world reserves will be completely consumed by 2020 AD. at this rate.

The energy consumption in the United States was 1.5 Q up to 1950. Figure 18 shows that in 1978 another 1.5 Q of energy will have been used.



Reported from Putnam, P. C., Energy in the Future, D. van Nostrand Co., Inc., New York (1953).

Figure 16. Estimated Efficiency of the Use of Energy.

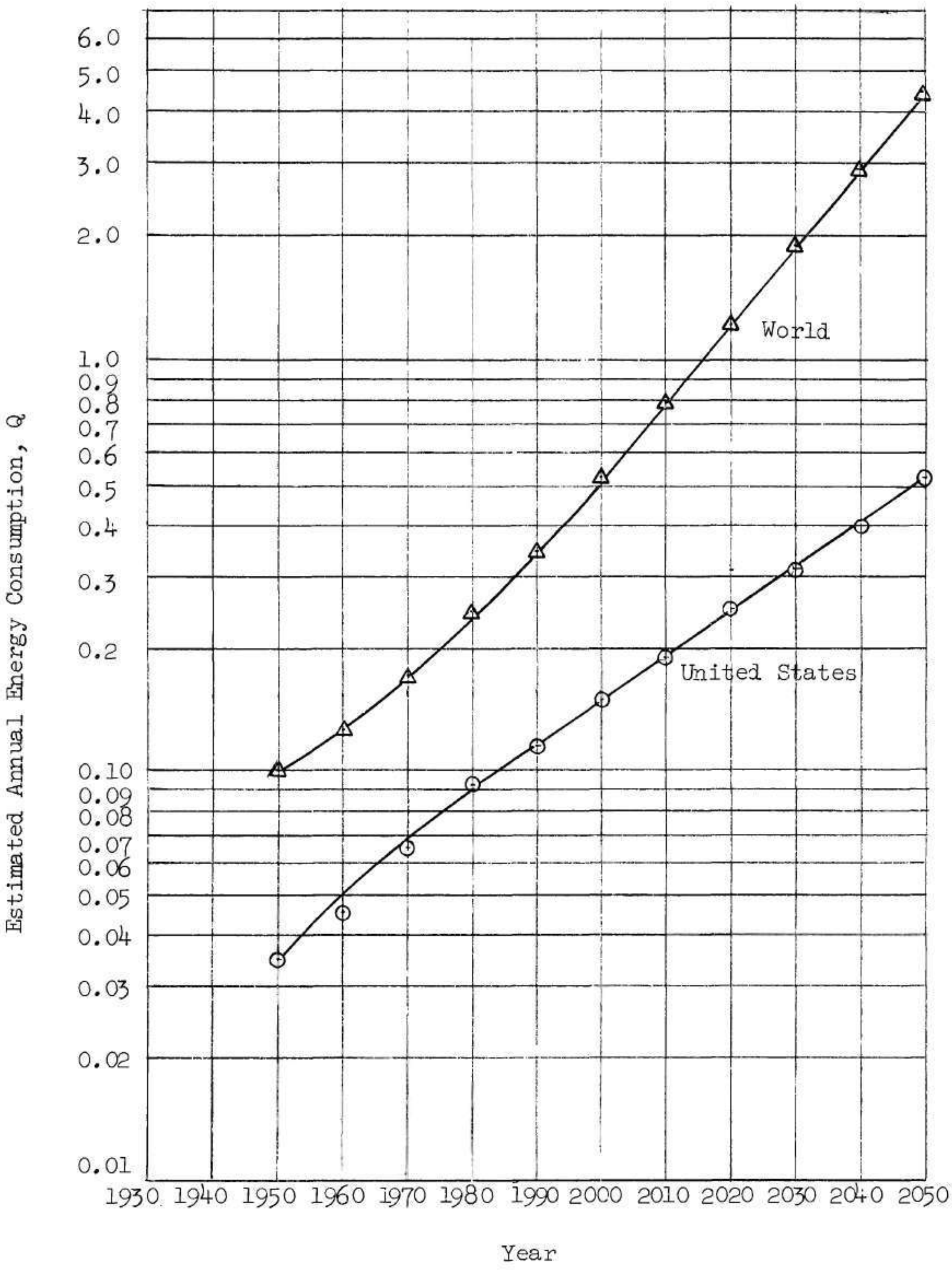


Figure 17. Estimated Annual Energy Consumption of the World and the United States.

Table 12. Estimated Annual Energy Consumption of the World

Year	Yearly Per Capita Demand BTU	Efficiency %	Yearly Per Capita Consumption BTU	Estimated Population Billions	Total Annual Consumption of Energy Q
1947	8.8×10^6	22	39.9×10^6	2.33	0.093
1950	9.6×10^6	23	41.6×10^6	2.40	0.100
1960	12.9×10^6	28	46.1×10^6	2.70	0.125
1970	17.3×10^6	31	55.8×10^6	3.10	0.173
1980	23.3×10^6	33	70.5×10^6	3.50	0.247
1990	31.2×10^6	35	89.0×10^6	3.90	0.347
2000	42.0×10^6	35	120.0×10^6	4.40	0.528
2010	56.3×10^6	36	156.2×10^6	5.10	0.797
2020	76.0×10^6	36	211.0×10^6	5.90	1.250
2030	101.8×10^6	36	283.0×10^6	6.70	1.900
2040	136.9×10^6	36	380.0×10^6	7.60	2.890
2050	184.0×10^6	36	510.0×10^6	8.79	4.480

Table 13. Estimated Annual Energy Consumption of the United States

Year	Yearly Per Capita Demand BTU	Efficiency %	Yearly Per Capita Consumption BTU	Estimated Population Millions	Total Annual Consumption of Energy Q
1947	63.8	29	220.0×10^6		
1950	70.0	30	233.0×10^6	150	0.0351
1960	93.6	34	275.0×10^6	170	0.0467
1970	126.0	37	340.0×10^6	190	0.0646
1980	169.0	40	423.0×10^6	220	0.0932
1990	196.0	41	478.0×10^6	240	0.115
2000	228.0	42	543.0×10^6	275	0.149
2010	265.0	43	616.0×10^6	310	0.191
2020	307.0	43	715.0×10^6	350	0.250
2030	356.0	44	809.0×10^6	390	0.315
2040	412.0	44	935.0×10^6	440	0.411
2050	480.0	45	$1,065.0 \times 10^6$	496	0.533

Table 14. Estimated Cumulative Energy
Consumption of the World

Year	Cumulative Energy Consumption Q
to 1950	13.0
1970	15.7
1990	20.9
2010	32.2
2030	59.2
2050	123.2

Table 15. Estimated Cumulative Energy
Consumption of the United States

Year	Cumulative Energy Consumption Q
to 1950	1.5
1970	2.5
1990	4.3
2010	7.4
2030	12.4
2050	20.7

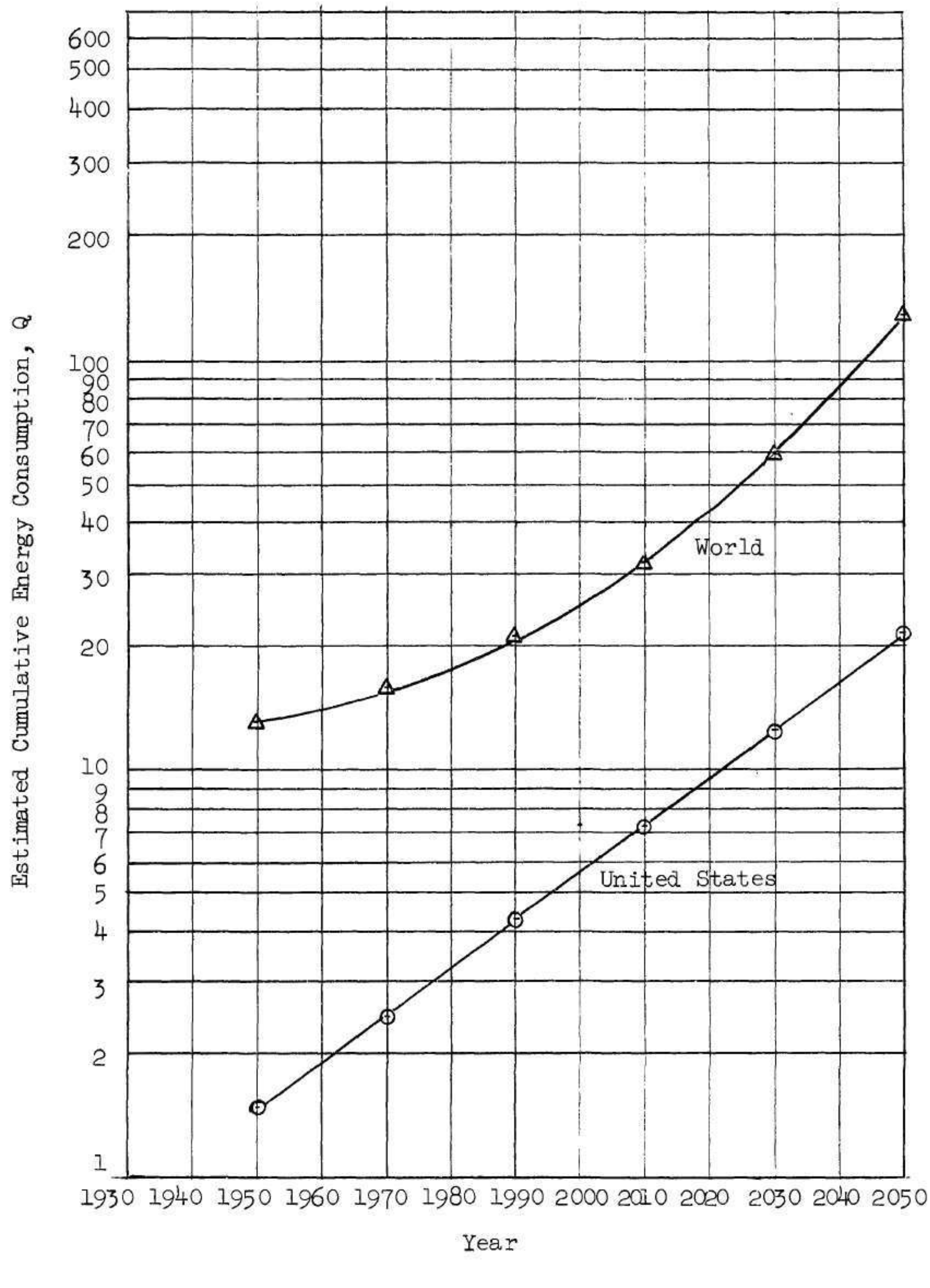


Figure 18. Estimated Cumulative Energy Consumption of the World and United States.

At this rate the economically recoverable reserves of the United States will be depleted by 2010 AD. An extrapolation of both curves gives 2060 AD and 2090 AD as the years in which the maximum reserves will have been consumed by the World and the United States, respectively. It is clear that other energy sources must be found that can take over part of the load by 2010 AD and most of it by 2100 AD. The extensive use of nuclear fuels might postpone these dates by approximately fifty to a hundred years, but after these have been consumed mankind will be faced with a serious energy problem.

The problem of providing food for the increasing population is no simple problem either. For food we depend upon crop land for edible plants, to some extent upon pasture land for meat, and upon the sea and inland waters for fish.

The earth has a land area of about 55 million square miles (106). Only 4 million square miles would make good crop land having the right temperature, rainfall, and soil quality (106). Another 2.2 million square miles is regarded as arable, but not suitable for intensive farming. If it is assumed that the yield of this land will be 50 per cent of that of the fertile land, then we have available the equivalent of 5.1 million square miles or 3.3 billion acres of land suitable for intensive cultivation. In addition to this approximately 5.1 billion acres of pasture land is available (107). Much of this land is timbered and perhaps 1 billion acres could be converted to crop land, bringing the total to 4.3 billion acres. If this land could be made to produce close to the best yields of today, it could support approximately 4.3 billion people, since one acre per person is probably the minimum for adequate dietary requirements. Based on the estimated population increase, the production of food could keep pace with the population until about 1995.

In the United States the situation is not much better. Approximately 350 million acres of the United States can be considered good crop land (108). In addition to this about 1000 million acres of pasture land is available (108). Assuming that 10 per cent of it can be converted to crop land, we arrive at a total of 450 million acres which could support 450 million people. Based on these assumptions and the assumed population increase it can be seen that the food supply in the United States will be adequate until about 2040 AD.

The figures indicate that the human race will shortly be faced with an energy problem and a food problem.

Several solutions to the energy problem are possible. The possibility exists that scientists will learn to control the fusion reaction which converts hydrogen into helium with the evolution of tremendous amounts of energy. The hydrogen contained in a cubic mile of sea water could then supply 1.14×10^{18} kw hrs of energy at an efficiency of 10 per cent (109). This amount of energy would satisfy our needs for a long time. However, it seems more likely that man will start using the direct energy from the sun on a much larger scale.

House heating with solar energy will probably soon be used to a large extent. Economic studies have indicated that solar heating is presently slightly more expensive than heating with cheap natural gas, but coal, oil, and propane heating costs can be reduced by use of solar energy. If house heating with solar energy materializes, a considerable load will be taken of the energy demand since at least a quarter of our fuel production is used for heating purposes. In less mecharized countries the fraction is even greater.

Use of solar energy for water heating will probably also become of much greater importance, especially when the standards of living of the now underdeveloped countries become higher. Economic evaluations show already pay-out times of between 2.4 and 4.5 years, which indicates that the use of these units can be justified economically in suitable regions. No doubt with our increasing knowledge of design and the rising costs of energy the future of the solar water heater will look even brighter.

To provide the increasing population with an adequate supply of gasoline in the future, coal might be hydrogenated to give liquid fuels. Another possibility would be to grow algae in large cultures and to convert these organisms into motor fuel by application of the Fischer-Tropsch synthesis. To provide enough fuel for the population of the United States by this method an area of about 35,000 square miles would be required, assuming an intermediate predicted yield of 35 dry tons per acre per annum (110). Fuel obtained in this manner would cost at least 10 cents per pound. The capital investment would also be high, but with additional research and development these costs would undoubtedly become lower.

Electricity could be provided by solar cells in the future. However, it appears that nuclear reactors can provide this power at a much lower cost unless the cost of the solar cells goes down drastically. The possibility exists, however, that electricity might be generated with these units in rural and remote areas where the construction of an atomic reactor would be prohibitively expensive.

To supply the growing population with adequate fresh water, use might be made of solar distillation. Stills have been improved so that they can produce fresh water at \$0.82 per thousand gallons at an investment of \$4.50 per daily gallon capacity. Using cheap plastics in place of glass, the operating cost might be reduced to \$0.68 and the investment to \$2.75 per daily gallon capacity.

To provide food for the ever-increasing population it appears that the present arable land will be cultivated more and more intensively. Adequate weed, insect, and disease control in addition to better fertilizer and soil technology are expected to increase the yields to the best present productions. Additional crop land might be obtained by irrigating arid land with water produced by solar distillation of brackish or sea water. Also algae might be grown on a large scale to increase the food production. Operating costs would be about \$0.25 per pound in the present stage of development which put algae out of consideration for the present, at least. But, it appears that this cost could be lowered appreciably with adequate research to obtain the maximum yields.

The use of solar energy to supply the space traveler with food, oxygen, and energy has been discussed in Chapter XI. Also the application of solar energy to propel future space ships has been treated. It is the opinion of the writer that large scale use will be made of solar energy for space travel.

It is impossible to predict how food and energy will be provided for the population of the world 100 years from now. It is also impossible to predict accurately how long the population of the world will increase and what the limit will be, or what factors will be predominant in imposing this limit. One fact, however, can be predicted with certainty and that is that solar energy will become of increasing importance as time goes on.

CHAPTER XIII

CONCLUSIONS

Conclusions reached as a result of this study are as follows:

1. Some applications of solar energy are already economical under suitable circumstances. These applications include·

(a) Solar distillation,

(b) Solar water heating, and

(c) Solar house heating.

2. Research and development and the rising costs of fossil fuels will make other applications more attractive, and will increase the use of solar energy.

3. The fossil fuel reserves of the United States will be depleted by 2090 AD and the fuel reserves of the World as a whole by 2060 AD, if no new sources of energy are found and the fossil fuels continue to constitute the major source of energy.

4. It is apparent that the problem of providing enough energy for the growing population will become serious in the immediate future, and that solutions to this problem must be found.

5. The energy problem may be postponed for about 100 years through an expansion of facilities for generating power via atomic reactors, but even so the problem will arise again.

6. No one can predict what new developments will be uncovered in the future, but, as seen at the present, the probabilities are that research will merely postpone the problem. Since the energy of the sun will last for a long time, it seems that the only ultimate solution to

the energy problem is through the use of solar energy.

7. The amount of arable land will be insufficient so support the growing world population after about 1995 AD.

8. The production of food in the United States will be adequate until about 2040 AD. Then this country will have a food problem.

9. The ultimate solution to the food problem is the intensive cultivation of food sources such as algae that can be produced completely under human control.

CHAPTER XIV

RECOMMENDATIONS

The following recommendations are made for future work:

1. Meteorological research is needed so that better advice on localities, design, and orientation can be given to those who plan to use the sun's energy.

2. The use of cheap materials, such as plastics and aluminum foils, in the design of solar equipment should be investigated.

3. More information is needed on the light transmission and the weathering of cheap plastics.

4. The reflection and the weathering of thin metal foils should be investigated.

5. Storage of low temperature energy for house heating has received some attention, but a great deal more is necessary. An important point which has not been considered is the storage for long periods of time, i.e. energy received in the summer stored for use in the winter.

6. Another possibility that apparently has not received any consideration is the storage of high temperature energy. If this energy could be stored economically, it would greatly expand the use of solar engines and solar furnaces.

7. More emphasis should be placed on the intensive cultivation of algae. It appears that algae utilize the light of the sun more efficiently if they are exposed to light flashes of short duration. Studies should be

made to determine the optimum light intensity and the optimum duration of the light flashes.

8. Presently, algae installations must be cooled because the strains of algae used cannot tolerate the relatively high temperatures which are produced in the containers by sunlight. It appears, however, that a strain can be produced which will stand the higher temperatures so that the expensive cooling facilities can be eliminated. Therefore, a study should be made to determine if a high temperature strain of algae can be produced by breeding and selection.

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